Supplemental Material

CBE—Life Sciences Education

Price et al.

Supplementary Information for

A Detailed Characterization of the Expert Problem-Solving Process in Science and Engineering; Guidance for Teaching and Assessment

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This file includes:

Supplementary text: interview protocol, full decisions list, notes on trends in specific decisions
Legends for Tables S1 and S2
Legend for Dataset S1

Other supplementary materials for this manuscript include the following:

Tables S1 and S2
Dataset S1

Supplementary Information Text

Supplementary Methods

Complete semi-structured interview protocol

Notes:

Inspired by the "Critical Decision Method" protocol of cognitive task analysis (Crandall et al., 2006)

Semi-structured interview with many questions optional, depending on course of interview. Questions in bold were prioritized, so were usually asked.

Aside from initial prompts and prompts to keep them on target or to provide enough detail, interviewers will say very little during the story telling part of the interview, then will ask elaboration and deepening questions to follow up.

Introduction

We are interviewing you as part of a project to identify how experts think as they solve problems during their research/work. Our goal is to identify what students ought to be learning to do in order to improve education. So today we'd like to learn how you solve problems by having you recall a problem you have solved or project you've completed, and walk us through all the detailed steps. Particularly focus on the detailed decisions you made when solving the problem.

Eliciting the scenario/problem:

1. **So, think about a problem you've solved in your work (or project you've completed). Choose a problem in which you can remember all the detailed steps and decisions.**

2. Then please walk me/us through how you went about solving that problem: What were the goals you were trying to achieve? What did you do step by step? What decisions did you make?

Optional guidance questions to ask during story

a. If they're having trouble thinking of a problem:
    i. What is the most recent paper you've published/project you've worked on? How did you go about tackling that project?
    ii. What was a particularly challenging research problem (or design problem or work problem) you've dealt with?
b. If they need more guidance starting to tell the story:
    i. What was the first decision you needed to make?
    ii. What did you do first?
        1. What did you do next? (phrase appropriately to respond to something in their narrative if they've stalled)
    iii. You mentioned X goal, what did you do to accomplish that?
    iv. What were the most important things for you to think about?

c. If they give too short or high-level of an account
    i. (Especially at beginning to set the tone) probe for decisions made that were unstated: How did you decide X, that you just mentioned?
    ii. What led to your decision X?
    iii. What did you mean by X?

Check-in, clarifications, and elaboration (may be asked during story, as needed):

3. Ask for clarification about parts of the story that were unclear
    a. In particular, if they used specific words like "model," ask them to elaborate on their meaning of the term.
        i. Ask for examples of where and how they used term/models (if not already stated) – elaborating on meaning may be best done through examples.
4. Ask for elaboration on parts of the story that were glossed over (can interrupt story to ask, but give them time to get there themselves)
    a. How did you decide…?
    b. What led to your decision X?
    c. Why did (or didn't) you…?
    d. What did you do next?

More specific elaboration questions

Note: Can ask after story telling if they weren't naturally covered, or don't need to ask if they came up on their own. Can also bring up during story to help move story along or away from excess detail or attempts to teach. Prioritize bolded questions (combine "elaboration" and "deepening").

5. **How did you decide to tackle the problem in the first place?**
6. You said you did X first; how did you decide to tackle that aspect first?
    a. Or more general (preferred): How did you decide which way to go first?
7. You said you chose X method/route; how/why did you pick that method over other possible methods?
    a. Or more general (preferred): Why did you choose the path or methods you chose?
8. What information or data did you need to collect?
    a. Where did you get this information?
    b. What did you do with this information?
9. How did you interpret the results you collected (at X point)?
10. Were there other solutions you considered?
    a. How did you differentiate the possible solutions?

"Deepening" questions about the whole process

11. **What did you think were critical decisions you made during the process?**

    a. If they don't mention a particular point of story that interviewer thinks involved critical decisions, can ask for elaboration about decisions made during that particular point
    b. What decisions were you given vs. that you made (or what were the parameters you had at the start)?
12. **What challenges did you encounter in solving the problem?**
    a. How did you deal with those challenges?
13. **What (if any) new knowledge or skills did you need to acquire for solving your problem?**
    a. How did you acquire those?
14. What tests or experiments did you run?
    a. How did you decide on them?
    b. How did you interpret the results? (or ask alternative about a specific point – question 8)
15. (optional) How does this connect with prior work you've done?
16. **How did you decide you had an adequate result (to publish paper/submit design, etc.)**
    a. How did you know you were done?
    b. When did you decide your design/solution/conclusion was satisfactory?
17. What are the implications (or next steps) for your project?
18. How were your findings/product received by the community?

<u>What-if scenarios:</u>

19. What alternative decisions could you have made (in general or at specific point X), and what might have happened differently?
20. **If your student/trainee had been solving this problem instead of you (or without your guidance), how do you think their approaches would have differed from yours?**

<u>Other questions about perspective on expertise in their field (if time)</u>

21. **What are particular difficulties in problem-solving you've noticed in people you have trained or mentored? (be specific)**
22. **How do you use models in your work?**
23. What do you see as differences between experts and novices?
24. What do you think was your particular expertise that made you successful (in solving this problem, and more generally in your career)?
25. What do you want your trainees to be able to do (While trainees? After they're done training?)?

Supplementary Text

Complete list of decisions-to-be made by experts when solving authentic problems

A. Selection and goals

1) **What is important in field?**

What are important questions or problems? Where is the field heading? Are there advances in the field that open new possibilities?

2) **Opportunity fits solver's expertise?**
   If and where are there gaps/opportunities to solve in field? Given experts' unique perspectives and capabilities, are there opportunities particularly accessible to them? (could involve challenging the status quo, questioning assumptions in the field)
3) **Goals, criteria, constraints?**
   What are the goals for this problem? Possible considerations include:
   a. What are the goals, design criteria, or requirements of the problem or its solution?
   b. What is the scope of the problem?
   c. What constraints are there on the solution?
   d. What will be the criteria on which the solution is evaluated?

B. Frame Problem

4) **Important features and info?**
   What are the important underlying features or concepts that apply? Could include:
   a. Which available information is relevant to solving and why?
   b. (when appropriate) Create/find a suitable abstract representation of core ideas and information Examples: physics – equation representing process involved, chemistry – bond diagrams/potential energy surfaces, biology – diagram of pathway steps.
5) **What predictive framework?**
   Which potential predictive frameworks to use? (decide among possible predictive frameworks or create framework) This includes deciding on the appropriate level of mechanism and structure that the framework needs to embody to be most useful for the problem at hand.
6) **Narrow down problem.**
   How to narrow down the problem? Often involves formulating specific questions and hypotheses.
7) **Related problems?**
   What are related problems or work seen before, and what aspects of their solving process and solutions might be useful in the present context? (may involve reviewing literature and/or reflecting on experience)
8) **Potential solutions?**
   What are potential solutions? (Based on experience and fitting some criteria for solution they have for a problem having general key features identified.)
9) **Is problem solvable?**
   Is the problem plausibly solvable and is solution worth pursuing given the difficulties, constraints, risks, and uncertainties?

C. Plan Process for Solving

10) **Approximations and simplifications.**
    What approximations or simplifications are appropriate? How to simplify the problem to make it easier to solve? Test possible simplifications/approximations against established criteria.
11) **Decompose into sub-problems.**

How to decompose the problem into more tractable sub-problems? (Independently solvable pieces with their own sub-goals.)

12) **Most difficult or uncertain areas?**
    Which are areas of particular difficulty and/or uncertainty in plan of solving process? Could include deciding:
    a. What are acceptable levels of uncertainty with which to proceed at various stages?
13) **What info needed?**
    What information is needed to solve the problem? Could include:
    a. What will be sufficient to test and distinguish between potential solutions?
14) **Priorities.**
    What to prioritize among many competing considerations? What to do first and how to obtain necessary resources?
    Considerations could include: What's most important? Most difficult? Addressing uncertainties? Easiest? Constraints (time, materials, etc.)? Cost? Optimization and trade-offs? Availability of resources? (facilities/materials, funding sources, personnel)
15) **Specific plan for getting information**.
    What is the specific plan for getting additional information? Includes:
    a. What are the general requirements of a problem-solving approach, and what general approach will they pursue? (often decided early in problem-solving process as part of framing)
    b. How to obtain needed information? Then carry out those plans (b.2). (This could involve many discipline and problem-specific investigation possibilities such as: designing and conducting experiments, making observations, talking to experts, consulting the literature, doing calculations, building models, or using simulations.)
    c. What are achievable milestones, and what are metrics for evaluating progress?
    d. What are possible alternative outcomes and paths that may arise during problem-solving process, both consistent with predictive framework and not, and what would be paths to follow for the different outcomes?

D. Interpret Information and Choose Solutions

16) **Calculations and data analysis.**
    What calculations and data analysis are needed? Then to carry those out.
17) **Represent and organize information.**
    What is the best way to represent and organize available information to provide clarity and insights? (usually this will involve specialized & technical representations related to key features of predictive framework)
18) **How believable is information?**
    Is information valid, reliable, and believable (includes recognizing potential biases)?
19) **Compare to predictions.**
    As new information comes in, particularly from experiments or calculations, how does it compare with expected results (based on their predictive framework)?
20) **Any significant anomalies?**
    If a result is different than expected, how should they follow up? (Requires first noticing the potential anomaly). Could involve deciding:

a. Does potential anomaly fit within acceptable range of predictive framework(s) (given limitations of predictive framework and underlying assumptions and approximations)?
b. Is potential anomaly an unusual statistical variation, or relevant data? Is it within acceptable levels of uncertainty?

21) **Appropriate conclusions?**
What are appropriate conclusions based on the data? (involves making conclusions and deciding if they're justified)

22) **What is the best solution?**
Deciding on best solution(s) involves evaluating and refining candidate solutions throughout problem-solving process. Not always narrowed down to a single solution. May include deciding:
a. Which of multiple candidate solutions are consistent with all available information and which can be rejected? (could be based on comparing data with predicted results)
b. What refinements need to be made to candidate solutions?

E. Reflect (ongoing)

23) **Assumptions + simplifications appropriate?**
Are previous decisions about simplifications and predictive frameworks still appropriate?
a. Do the assumptions and simplifications made previously still look appropriate considering new information? (reflect on assumptions)
b. Does predictive framework need to be modified? (Reflect on predictive framework.)

24) **Additional knowledge needed?**
Is additional knowledge/information needed? (Based on ongoing review of one's state of knowledge.) Could involve:
a. Is solver's relevant knowledge sufficient?
b. Is more information needed and if so, what?
c. Does some information need to be checked? (e.g. need to repeat experiment or check a different source?)

25) **How well is solving approach working?**
How well is the problem-solving approach working, and does it need to be modified, including do the goals need to be modified? (Reflect on strategy by evaluating progress toward solution)

26) **How good is solution?** How adequate is the chosen solution? (Reflect on solution) Includes ongoing reflection on potential solutions, as well as final reflection after selecting preferred solution. Can include:
a. Decide by exploring possible failure modes and limitations – "try to break" solution.
b. Does it "make sense" and pass discipline-specific tests for solutions of this type of problem?
c. Does it completely meet the goals/criteria?

F. Implications and Communications of Results

27) **Broader implications?**
What are the broader implications of the results, including over what range of contexts does the solution apply? What outstanding problems in field might it solve? What novel

predictions can it enable? How and why might this be seen as interesting to a broader community?

28) **Audience for communication?**
What is the audience for communication of work, and what are their important characteristics?

29) **Best way to present work?**
What is the best way to present the work to have it understood, and its correctness and importance appreciated? How to make a compelling story of the work?

G. **Non-Decision Themes: Ongoing Knowledge and Skill Development**

(30) **Stay up to date in field**
Staying up to date could include:
   a. Review literature, which does involve making decisions as to which is important.
   b. Learn relevant new knowledge (ideas and technology, from literature, conferences, colleagues, etc.)

(31) **Intuition and experience.**
Acquiring experience and associated intuition to improve problem-solving.

(32) **Interpersonal, teamwork**.
Includes navigating collaborations, team management, patient interactions, communication skills, etc., particularly as how these apply in the context of the various types of problem-solving processes.

(33) **Efficiency.**
Time management including learning to complete certain common tasks efficiently and accurately.

(34) **Attitude.**
Motivation and attitude to the task. Factors such as interest, perseverance, dealing with stress, confidence in decisions, etc.

Notes about Tables S3 and S4: discussion of trends in specific codes.

A few decisions were less likely to be mentioned in interviews, particularly in certain disciplines. See notes in supplemental table 3 for additional details.

- Decisions 1 and 2 (importance and gaps/opportunities). Mentioned less frequently, particularly where the problem was assigned to the expert (often in engineering or industry) or where the importance was implicit (often in medicine). For example, overall, decision 1 was mentioned in 61% of interviews, but that percentage increased to 94% when medicine and industry were excluded from the tabulation (see table S4).
- Decisions 27 (broader implications), 28 (audience), and 29 (present). Depended on the scope of the project being described and the expert's specific role in it, so these decisions had little relevance in some interviews and fields and were not mentioned. 29 was particularly dependent on field, being mentioned in 68% of interviews overall, but increasing to 94% if medicine and industry were excluded (see table S4).
- Decisions 9 (is the problem solvable). This decision is generally implicit in the fact that the expert picked the problem to describe in the interview (they had decided it was worth solving), but

often not mentioned. It was less likely to be coded in interviews in medicine, or other interviews where the problem was assigned to the expert. Often when 9 was mentioned explicitly, it was in the context of deciding not to pursue an approach, or when describing the decision that a specific aspect of a problem or question is not solvable.

- Decision 11 (decompose). The experts relatively seldom discussed decomposition explicitly, likely because it had become such a fundamental and automatic part of their problem-solving process. This was particularly true in medicine, where deciding how to decompose was rarely mentioned, although it is well established (and supported by our informal interviews) as being fundamental to how the medical diagnostic process is structured (e.g. thinking through organ systems). Overall, decision 11 was mentioned in 68% of interviews, but that increased to 76% if medicine were excluded (see table S4), and likely that is still a significant undercount of the true use judging from the informal interviews.
- Decision 17 (represent and organize information), and to a lesser extent 16 (calculations and data analysis). These usually came up explicitly in interviews only if/after the expert was asked how they arrived at conclusions. Without such prompting, the expert would typically describe the information they collected, and then what they interpreted or concluded from that information, without elaborating on how the data was analyzed unless asked. Thus 16 and/or 17 must have happened during this process, but we didn't have enough evidence to code for them. In medicine in particular, 16 and 17 were unlikely to be mentioned, because typically a doctor is provided with test results that are already analyzed by a lab or radiologist, so they do not have to make decisions themselves about how to analyze and represent the data. Overall, 16 was mentioned in 80% of interviews, but that increases to 96% if medicine was excluded (table S4).
- Decisions 18 (how believable is information?) and 20 (any significant anomalies?) were coded less frequently than some other decisions, probably because of the retrospective nature of the interviews. Depending on the problem context, experts may not have encountered significant anomalies or needed to question the validity of information, or they did not come up in the context of the interview, because by that point they had figured out any such behavior, and so in the retrospective process it no longer stood out as puzzling or unexpected.
- Reflection decisions 23 (reflect on assumptions) and 24 (reflect on knowledge) were coded less frequently than others because our coding of "reflection" required the expert to remember and relay their thinking process, in contrast to describing their actions which was the usual focus. In addition, to distinguish 24c from 13 (what information is needed?) and 15 (plan), we required some explicit evidence of reflection, such as statements about re-thinking or deciding to collect additional different information than in original plan.

We also noted some decisions that were particularly likely to co-occur, or in the context of the interview were completely intertwined. Our initial list had several decisions that we found nearly always co-occurred, and those we consolidated. However, some decisions were particularly likely to co-occur but were still mentioned separately a modest fraction of the time, so we kept those separate. We describe the most common of these below and see the additional notes in table 3.

- Decisions 23 (reflect on assumptions), 25 (reflect on strategy), 26 (reflect on solution). It was often difficult to distinguish between reflection decisions. In some cases, the method (approach) *was* the solution to a problem or sub-problem being discussed, so 25 and 26 were identical. In

other cases, reflection on solution or approach also required reflecting on assumptions, so 23 often co-occurred with 25 and 26.

- Decisions 3 (goals), 6 (narrow problem), and 11 (decompose). Each is a more specific aspect of refining the problem, and so they could be indistinguishable in an interview, depending on the coherence and detail of the interview.
- Decisions 14 (priorities), 3 (goals), 15 (plan), and 12 (particular difficulty). 14 was often co-coded with other decisions, because deciding on priorities involves the weighting of a variety of factors. Decisions about resources were often coded with 3 (regarding criteria or constraints). Decisions about which approaches to try first or which parts of the problem to approach first were often coded with 15 (plan) or 12 (particular difficulty), because the expert often plans to prioritize (or prioritize ways to avoid) the areas of difficulty identified in 12.
- Decisions 1 (importance), 2 (opportunity fits expertise), and 27 (broader implications). These require very similar cognitive processes, but at different parts of the problem-solving process. Given the structure of our interviews, they were often hard to distinguish. The experts often discussed the importance of the problem as it related to what opportunities there were to make progress that matched with their expertise, so 1 and 2 were frequently coded together. For 27, after discussing their process and solution to a problem, broader implications were often mentioned in the context of discussing their next steps in terms of goals and opportunities, thus 27 would lead to a new problem and a new round of 1 and 2. A subset of interviews had a specific 27 + 2 combination: The expert would describe their development of a new tool or theory, then move on to talking about what problem(s) they could solve using this tool. This also involved 9, in that they were examining what current outstanding problems in the field would now be tractable.

A key feature of the interviews that is not captured by the decisions list is the iterative nature of the decisions being made. Most of the decisions were mentioned multiple times in each interview. Sometimes they were separated into discrete cycles of going through a set of decisions to solve one component of the problem, then repeating to solve a different component of the problem. Often, reflection or an unexpected result or difficulty would trigger iteration back to earlier steps, where the expert would try a different approach at solving the problem or to refine the goals of the problem and solve a modified problem. The experts would also describe problems within problems, for example they would have a bigger-picture problem of trying to answer a scientific question or create a tool, but would also describe in detail the problem-solving process involved in troubleshooting a technical aspect of one of the steps needed in the bigger problem.

Table S1. (separate file)

Final coding tabulation of decisions that occurred in each semi-structured interview.

Table S2. (separate file)

Notes on complete problem-solving decisions list, and examples of each decision.

Data S1. (separate file)

Collection of semi-structured interview transcripts (with redactions for privacy) from subset of experts who agreed to have their interview transcript published.

SI References

1. Crandall, B., Klein, G. A., Hoffman, R. R. (2006). *Working Minds: A Practitioner's Guide to Cognitive Task Analysis*. MIT Press.

Key: y = mentioned, n = not mentioned, i = implied. **Position type. Faculty unless specified**	**in % of interviews (explicit)**	**in % of interviews including implied**	**% exclud med**	**% exclud med&indus**	phys + chemE-theory	phys theory	biochem staff	earth sci	molec bio-acad + ind	chem	bio senior pdoc	phys - exper	mechE	cell bio	bio senior pdoc	immu nol	ecol	phys - exper	phys + elecE theor
% of decisions (1-29, not themes) mentioned by faculty -					90	100	97	93	97	86	90	100	93	83	90	83	93	90	83
Selection and goals																			
1) **What is important in field?** What are important questions or	48	61	76	94	i	y	y	y	y	y	i	y	y	y	i	n	y	y	y
2) **Opportunity fits solver's expertise?** If and where are there gaps/opportunities to solve in field? Given their unique perspectives and capabilities, are there opportunities particularly accessible to them? (could involve challenging the status quo, questioning assumptions in the field)	71	77	88	94	y	y	y	y	y	y	y	y	y	n	y	y	y	y	y
3) **Goals, criteria, constraints?** What are your goals for this problem? Possible considerations: a. What are goals, design	97	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Frame Problem																			
4) **Important features and info?** What are the important underlying features or concepts that apply? e.g. : a. Which available information is relevant to solving and why? b. (when appropriate) Create/find a suitable abstract representation of core ideas and information Examples: physics – equation, chemistry – bond diagrams/potential energy surfaces, biology – diagram of pathway steps)	100	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
5) **What predictive framework?** Which potential predictive frameworks to use? (decide among possible predictive frameworks, or create frameworks) This includes deciding on the appropriate level of mechanism the framework needs to embody for the problem at hand.	97	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
6) **Narrow down problem.** How to narrow down the problem? Often involves formulating specific questions and hypotheses.	97	97	96	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
7) **Related problems?** What are related problems or work seen before, and what aspects of their solving process and solutions might be useful in the present context? (may involve reviewing literature and/or reflecting on experience).	97	97	96	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
8) **Potential solutions?** What are potential solutions? (Based on	100	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
9) **Is problem solvable?** Is the problem plausibly solvable and is solution worth pursuing given the difficulties, constraints, risks, and uncertainties?	61	74	80	75	i	y	y	y	y	y	y	i	n	n	y	y	n	y	n
Plan Process for Solving																			
10) **Approximations and simplifications.** What approximations or simplifications are appropriate? How to simplify the problem to make it easier to solve? Test simplification/approximations against established criteria.	77	81	80	81	y	y	y	y	y	n	y	y	y	n	i	n	y	y	y
11) **Decompose into sub-problems.** How to decompose the	42	68	76	88	i	y	y	n	y	i	y	i	y	y	y	i	y	i	n
12) **Most difficult or uncertain areas?** Which are areas of particular difficulty and/or uncertainty in solving process? Could include deciding: a. What are acceptable levels of uncertainty with which to proceed at various stages?	87	90	88	94	y	y	y	y	y	n	y	y	y	i	y	y	y	y	y
13) **What info needed?** What information is needed to solve the problem? What will be sufficient to test and distinguish between potential solutions?	97	100	100	100	y	y	y	i	y	y	y	y	y	y	y	y	y	y	y

Key: y = mentioned, n = not mentioned, i = implied. _____ **Position type. Faculty unless specified**	**in % of interviews (explicit)**	**in % of interviews including implied**	**% exclud med**	**% exclud med&i ndus**	phys + chemE-theory	phys theory	biochem staff	earth sci	molec bio-acad + ind	chem	bio senior pdoc	phys - exper	mechE	cell bio	bio senior pdoc	immu nol	ecol	phys - exper	phys + elecE theor
14) **Priorities.** What to prioritize among many competing considerations? What to do first and how to obtain necessary resources? Considerations could include: What's most important? Most difficult? Addressing uncertainties? Easiest? Constraints (time, materials, etc.)? Cost? Optimization and trade-offs? Availability of resources? (facilities/materials, funding sources, personnel)	81	87	84	81	n	y	y	y	y	n	y	y	y	y	n	y	y	y	i
15) **Specific plan for getting information.** What is the plan for getting additional information? Includes: a. What are the general requirements of a problem-solving approach, and what general approach will they pursue? (often decided early in problem solving process as part of framing) b. How to obtain needed information? Then carry out those plans (b.2). (This could involve many discipline and problem-specific possibilities such as: designing and conducting	97	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Interpret Information and Choose Solutions																			
16) **Calculations and data analysis.** What calculations and data analysis are needed? Then to carry those out.	68	81	96	94	y	y	y	y	y	y	y	y	y	n	i	y	y	y	y
17) **Represent and organize information.** What is the best way to represent and organize available information to provide clarity and insights? (usually this will involve specialized & technical representations related to key features of predictive framework)	45	68	80	94	y	y	y	y	i	i	y	y	i	i	y	n	i	y	y
18) **How believable is information?** Is information valid, reliable, and believable? What potential biases?	74	77	72	88	y	y	y	y	y	y	y	y	y	y	n	i	y	y	n
19) **Compare to predictions.** As new information comes in, particularly from experiments or calculations, how does it compare with expected results (based on their predictive framework)?	94	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
20) **Any significant anomalies?** If a result is different than expected, how should they follow up? (Requires first noticing the potential anomaly). e.g.: a. Does potential anomaly fit within acceptable range of predictive framework(s) (given limitations of predictive framework and underlying assumptions and approximations)? b. Is potential anomaly an unusual statistical variation, or relevant data? Within reasonable uncertainty?	71	71	68	75	n	y	y	y	y	y	n	y	y	y	y	y	n	n	y
21) **Appropriate conclusions?** What are appropriate conclusions based on the data? (involves making conclusions and deciding if they're justified)	94	97	96	94	n	y	y	y	y	y	y	y	y	y	y	y	y	y	y
22) **What is the best solution?** Involves evaluating and refining candidate solutions throughout problem solving process. May include deciding: a. Which of multiple candidate solutions are consistent with all available information and which can be rejected? (could be based on comparing data with predicted results) b. What refinements need to be made to candidate solutions?	94	97	96	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Reflect (ongoing)																			

Key: y = mentioned, n = not mentioned, i = implied. **Position type. Faculty unless specified**	**in % of interviews (explicit)**	**in % of interviews including implied**	**% exclud med**	**% exclud med&i ndus**	phys + chemE-theory	phys theory	biochem staff	earth sci	molec bio-acad + ind	chem	bio senior pdoc	phys - exper	mechE	cell bio	bio senior pdoc	immu nol	ecol	phys - exper	phys + elecE theor
23) **Assumptions + simplifications appropraite?** Are previous decisions about simplifications and predictive frameworks still appropriate? a. Do the assumptions and simplifications made previously still look appropriate in light of new information? (reflect on assumptions) b. Does predictive framework need to be modified? (Reflect on predictive framework.)	68	77	72	75	y	y	y	n	y	y	y	i	y	y	n	n	y	y	y
24) **Additional knowledge needed?** Is additional knowledge/information needed? (Based on ongoing review of one's state of knowledge.) Could involve: a. Is solver's relevant knowledge sufficient? b. Is more information needed and if so, what? c. Does some information need to be checked? (e.g. need to repeat experiment or check a different source?)	68	84	88	88	i	y	y	y	y	y	y	y	i	y	y	n	y	y	n
25) **How well is solving approach working?** How well is the problem solving approach working and does it need to be modified, including do the goals need to be modified? (Reflect on strategy by evaluating progress toward solution)	90	94	92	94	y	y	y	y	y	y	y	y	n	y	y	y	y	y	y
26) **How good is solution?** How well does the chosen solution hold? (Reflect on solution) e.g.: a. Decide by exploring possible	97	100	100	100	y	y	y	y	i	y	y	y	y	y	y	y	y	y	y
Implications and communications of results																			
27) **Broader implications?** What are the range of contexts where solution applies, and what are the broader implications? What outstanding problems in field might it solve? What novel predictions can it enable? How and why might this be interesting to a broader community?	55	65	72	81	y	y	n	y	i	y	n	y	y	y	y	i	y	y	n
28) **Audience for communicatioN?** What is the audience for communication, and what are their important characteristics?	42	55	60	63	y	y	i	y	n	n	n	y	y	n	y	y	i	n	y
29) **Best way to present work?** How to make a compelling story where work is understood and its correctness and importance appreciated?	65	68	72	94	y	y	y	y	i	y	y	y	y	y	y	y	y	n	y
Ongoing knowledge and skill development Note: these are NOT part of the expert problem solving *decisions*																			
(30) **Stay up to date in field**, including: a. Review literature, which involves making decisions as to which is important. b. Learn relevant new knowledge (ideas and technology, from literature, conferences, colleagues, etc.)	84	84	84	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
(31) **Intuition and experience.** Acquiring experience and associated intuition to improve problem solving.	71	77	72	69	n	y	n	y	y	i	n	y	y	i	y	n	n	y	y
(32) **Interpersonal, teamwork.** Interpersonal skills: Navigating collaborations, team management, patient interactions, communication skills, etc. and how are relevant to various types of problem-solving processes	100	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
(33) **Efficiency**. Time management and learning to complete certain common tasks efficiently and accurately.	26	32	36	44	n	y	n	i	y	n	y	n	n	i	n	n	n	n	y
(34) **Attitude**. Motivation and attitude. Factors such as interest, perseverance, dealing with stress, confidence in decisions, etc.	65	68	64	75	n	y	y	y	y	y	y	n	y	y	y	n	n	i	y

Key: y = mentioned, n = not mentioned, i = implied. **Position type. Faculty unless specified**	**in % of interviews (explicit)**	**in % of interviews including implied**	**% exclud med**	**% exclud med&indus**	chem	electE indus3	earth sci indus	mech E indus + gov	CS indus	molec bio indus	electE indus2	electE indus1	chem E indus 2	chem E indus 1	med1	med2	med3	med4 surgry	med5	med6 oncol
% of decisions (1-29, not themes) mentioned by faculty -					93	76	86	86	83	90	83	76	76	66	76	69	69	86	83	72
Selection and goals																				
1) **What is important in field?** What are important questions or	48	61	76	94	y	y	n	i	n	y	y	n	n	n	n	n	n	n	n	n
2) **Opportunity fits solver's expertise?** If and where are there gaps/opportunities to solve in field? Given their unique perspectives and capabilities, are there opportunities particularly accessible to them? (could involve challenging the status quo, questioning assumptions in the field)	71	77	88	94	y	y	y	n	y	i	y	y	n	y	n	n	n	y	i	n
3) **Goals, criteria, constraints?** What are your goals for this problem? Possible considerations: a. What are goals, design	97	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	i	y	y
Frame Problem																				
4) **Important features and info?** What are the important underlying features or concepts that apply? e.g. : a. Which available information is relevant to solving and why? b. (when appropriate) Create/find a suitable abstract representation of core ideas and information Examples: physics – equation, chemistry – bond diagrams/potential energy surfaces, biology – diagram of pathway steps)	100	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
5) **What predictive framework?** Which potential predictive frameworks to use? (decide among possible predictive frameworks, or create frameworks) This includes deciding on the appropriate level of mechanism the framework needs to embody for the problem at hand.	97	100	100	100	y	y	y	y	y	y	i	y	y	y	y	y	y	y	y	y
6) **Narrow down problem.** How to narrow down the problem? Often involves formulating specific questions and hypotheses.	97	97	96	100	y	y	n	y	y	y	y	y	y	y	y	y	y	y	y	y
7) **Related problems?** What are related problems or work seen before, and what aspects of their solving process and solutions might be useful in the present context? (may involve reviewing literature and/or reflecting on experience).	97	97	96	100	y	y	n	y	y	y	y	y	y	y	y	y	y	y	y	y
8) **Potential solutions?** What are potential solutions? (Based on	100	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
9) **Is problem solvable?** Is the problem plausibly solvable and is solution worth pursuing given the difficulties, constraints, risks, and uncertainties?	61	74	80	75	y	y	y	n	y	y	y	y	i	y	y	n	n	i	n	y
Plan Process for Solving																				
10) **Approximations and simplifications.** What approximations or simplifications are appropriate? How to simplify the problem to make it easier to solve? Test simplification/approximations against established criteria.	77	81	80	81	y	y	y	y	y	y	n	y	y	n	y	y	y	n	y	y
11) **Decompose into sub-problems.** How to decompose the	42	68	76	88	y	n	n	y	y	y	n	i	y	n	n	n	n	i	i	n
12) **Most difficult or uncertain areas?** Which are areas of particular difficulty and/or uncertainty in solving process? Could include deciding: a. What are acceptable levels of uncertainty with which to proceed at various stages?	87	90	88	94	y	n	y	y	y	y	y	y	y	n	y	y	y	y	y	y
13) **What info needed?** What information is needed to solve the problem? What will be sufficient to test and distinguish between potential solutions?	97	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y

Key: y = mentioned, n = not mentioned, i = implied. Position type. Faculty unless specified	in % of interviews (explicit)	in % of interviews including implied	% excluded	% excluded&indus	chem	electE indus3	earth sci indus	mechE indus + gov	CS indus	molec bio indus	electE indus2	electE indus1	chemE indus 2	chemE indus 1	med1	med2	med3	med4 surgry	med5	med6 oncol
14) **Priorities.** What to prioritize among many competing considerations? What to do first and how to obtain necessary resources? Considerations could include: What's most important? Most difficult? Addressing uncertainties? Easiest? Constraints (time, materials, etc.)? Cost? Optimization and trade-offs? Availability of resources? (facilities/materials, funding sources, personnel)	81	87	84	81	y	y	y	y	y	y	n	y	y	y	y	y	y	i	y	y
15) **Specific plan for getting information.** What is the plan for getting additional information? Includes: a. What are the general requirements of a problem-solving approach, and what general approach will they pursue? (often decided early in problem solving process as part of framing) b. How to obtain needed information? Then carry out those plans (b.2). (This could involve many discipline and problem-specific possibilities such as: designing and conducting	97	100	100	100	y	y	y	y	y	y	y	y	y	i	y	y	y	y	y	y
Interpret Information and Choose Solutions																				
16) **Calculations and data analysis.** What calculations and data analysis are needed? Then to carry those out.	68	81	96	94	y	y	y	y	i	i	y	y	y	y	n	n	n	i	n	n
17) **Represent and organize information.** What is the best way to represent and organize available information to provide clarity and insights? (usually this will involve specialized & technical representations related to key features of predictive framework)	45	68	80	94	y	n	y	n	i	n	y	y	n	i	n	n	n	n	y	n
18) **How believable is information?** Is information valid, reliable, and believable? What potential biases?	74	77	72	88	y	n	y	n	n	y	y	n	y	n	y	y	y	y	y	y
19) **Compare to predictions.** As new information comes in, particularly from experiments or calculations, how does it compare with expected results (based on their predictive framework)?	94	100	100	100	y	i	y	y	y	y	y	y	y	i	y	y	y	y	y	y
20) **Any significant anomalies?** If a result is different than expected, how should they follow up? (Requires first noticing the potential anomaly). e.g.: a. Does potential anomaly fit within acceptable range of predictive framework(s) (given limitations of predictive framework and underlying assumptions and approximations)? b. Is potential anomaly an unusual statistical variation, or relevant data? Within reasonable uncertainty?	71	71	68	75	y	n	y	y	y	y	n	n	y	n	y	y	y	y	y	n
21) **Appropriate conclusions?** What are appropriate conclusions based on the data? (involves making conclusions and deciding if they're justified)	94	97	96	94	y	y	y	y	y	y	i	y	y	y	y	y	y	y	y	y
22) **What is the best solution?** Involves evaluating and refining candidate solutions throughout problem solving process. May include deciding: a. Which of multiple candidate solutions are consistent with all available information and which can be rejected? (could be based on comparing data with predicted results) b. What refinements need to be made to candidate solutions?	94	97	96	100	y	i	y	y	y	y	y	n	y	y	y	y	y	y	y	y
Reflect (ongoing)																				

Key: y = mentioned, n = not mentioned, i = implied. **Position type. Faculty unless specified**	**in % of interviews (explicit)**	**in % of interviews including implied**	**% exclud med**	**% exclud med&indus**	chem	electE indus3	earth sci indus	mech E indus + gov	CS indus	molec bio indus	electE indus2	electE indus1	chem E indus 2	chem E indus 1	med1	med2	med3	med4 surgry	med5	med6 oncol
23) **Assumptions + simplifications appropraite?** Are previous decisions about simplifications and predictive frameworks still appropriate? a. Do the assumptions and simplifications made previously still look appropriate in light of new information? (reflect on assumptions) b. Does predictive framework need to be modified? (Reflect on predictive framework.)	68	77	72	75	n	y	y	y	y	y	n	i	n	n	y	y	y	i	y	y
24) **Additional knowledge needed?** Is additional knowledge/information needed? (Based on ongoing review of one's state of knowledge.) Could involve: a. Is solver's relevant knowledge sufficient? b. Is more information needed and if so, what? c. Does some information need to be checked? (e.g. need to repeat experiment or check a different source?)	68	84	88	88	y	y	y	y	y	y	i	i	i	n	y	y	y	n	y	n
25) **How well is solving approach working?** How well is the problem solving approach working and does it need to be modified, including do the goals need to be modified? (Reflect on strategy by evaluating progress toward solution)	90	94	92	94	y	y	y	y	y	y	y	y	y	n	y	y	y	i	y	y
26) **How good is solution?** How well does the chosen solution hold? (Reflect on solution) e.g.: a. Decide by exploring possible	97	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Implications and communications of results																				
27) **Broader implications?** What are the range of contexts where solution applies, and what are the broader implications? What outstanding problems in field might it solve? What novel predictions can it enable? How and why might this be interesting to a broader community?	55	65	72	81	y	n	i	y	n	y	y	n	n	y	n	n	n	y	y	n
28) **Audience for communicatioN?** What is the audience for communication, and what are their important characteristics?	42	55	60	63	n	y	i	y	n	n	y	n	n	y	n	n	n	y	n	i
29) **Best way to present work?** How to make a compelling story where work is understood and its correctness and importance appreciated?	65	68	72	94	y	n	y	y	n	n	y	n	n	n	y	n	n	y	n	y
Ongoing knowledge and skill development Note: these are NOT part of the expert problem solving *decisions*																				
(30) **Stay up to date in field**, including: a. Review literature, which involves making decisions as to which is important. b. Learn relevant new knowledge (ideas and technology, from literature, conferences, colleagues, etc.)	84	84	84	100	y	n	y	y	n	y	y	n	n	y	y	n	y	y	y	y
(31) **Intuition and experience.** Acquiring experience and associated intuition to improve problem solving.	71	77	72	69	y	n	y	y	y	y	y	y	y	n	y	y	y	y	y	y
(32) **Interpersonal, teamwork.** Interpersonal skills: Navigating collaborations, team management, patient interactions, communication skills, etc. and how are relevant to various types of problem-solving processes	100	100	100	100	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
(33) **Efficiency**. Time management and learning to complete certain common tasks efficiently and accurately.	26	32	36	44	y	n	n	n	n	y	n	y	n	n	n	n	n	n	y	n
(34) **Attitude**. Motivation and attitude. Factors such as interest, perseverance, dealing with stress, confidence in decisions, etc.	65	68	64	75	y	y	n	y	n	y	y	n	n	n	y	n	y	y	y	y

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
Selection and goals						
1) **What is important in field?** What are important questions or problems? Where is the field heading? Are there advances in the field that open new possibilities?	This decision was coded less often than most decisions, likely because whether an expert mentioned it depended on the problem described, their role in solving it, and the context of the interview. It was coded particularly less frequently in fields where the problem was assigned to the expert (often in engineering) or where the importance was implicit (often in medicine).	61	(physics) If you could find a topological superconductor, you could use it to build a much better quantum computer than any of the current implementations. This is broadly known to be true. But basically you need to find the right type of system to do it with and that system doesn't exist yet.	(biology) But then I quickly got quite interested in it because it became clear once I sequenced it that it had potential transmembrane domains in it. So it turned out to be a protein of the nuclear envelope, which we showed, and which made me more interested in it. Because I felt at that time there were all sorts of question about where something that was impacting export was actually located.	(chemistry) Structural control of a polymer is kind of the edge of where polymer chemistry is. For the past several decades, I would say, people have been focused on being able just to make this long chain of things and being able to do it reproducibility and reliably. And now people think, oh, it would be nice to kind of explore sort of these, more like smaller molecular impacts on the function of the polymer. And so that's where the chemistry is really interesting because. One aspect of chemistry is how molecular structure affects the function of a given thing.	
2) **Opportunity fits solver's expertise?** If and where are there gaps/opportunities to solve in field? Given experts' unique perspectives and capabilities, are there opportunities particularly accessible to them? (could involve challenging the status quo, questioning assumptions in the field)	Similar to 1, this decision was coded less often, depending on the field and the nature of the problem. When 1 and 2 did occur, they were often coded together because many experts discussed the importance of the problem as it related to the opportunities to make progress that matched their expertise. 1 and 2 were also closely related to 27 as well (see notes for 27).	77	(electrical engineering) *(coded as 1 and 2, and leads into 3)* Asked them "What can [My company] do for you?" And they said, "You can put phosphors in glass." ... [description of features of LED's and how phosphors are used to change their color to get white light out] … [Client] makes high power LEDs for things like headlights. so they need the material that holds the phosphor at very high temperatures. good thermal conductivity.	(medicine) but the association between the renal anomalies and the uterine anomalies is often not appreciated. … [general description of history and symptoms] … So putting those things together with the renal history and the possibility of the anomalies is something that - because I'm quite aware of those unusual anomalies is a diagnosis I am often the first one to make.	(physics) motivated by the fact that in quantum mechanics information doesn't have to be local—it doesn't have to be stored in individual atoms—entanglement—but usually in nature things are local—interact with what's near them—forces are local, so that kind of limits how well you can explore quantum mechanics, so we actually have this setup where you can use photons to convey information across long distances in a cloud of atoms	
3) **Goals, criteria, constraints?** What are your goals for this problem? Possible considerations include: a. What are the goals, design criteria, or requirements of the problem or its solution? b. What is the scope of the problem? c. What constraints are there on the solution? d. What will be the criteria on which the solution is evaluated?	A "problem" is an authentic, complex, problem encountered in the expert's work.	100	(biology) the ultimate goal was to figure out a way to get efficient targeted genetic engineering of a native human gene. That was the end. That was sort of the end goal at the very end of the day.	(chemical engineering) And I can test that in the on shore environment, but in the off-shore environment, the rig, well in this particular case the rig was probably only a, a total spend of maybe $150,000-$200,000 a day, which is cheap. In the deep water that can be $1 million a day, and you have the problem of putting a temporary facility on something out in the water, and there's a whole bunch of safety…environmental and safety constraints. Because there's no place to put a tank and store the stuff.	(medicine) There will be some cancer cells in many cases that the surgeon just can't get. So if we give chemotherapy and radiation we can eliminate the rest of the cells from the body. But as you can imagine this poses all kinds of really thorny and difficult problems for doctors.	
Frame Problem						

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
4) **Important features and info?** What are the important underlying features or concepts that apply? Could include: a. Which available information is relevant to solving and why? b. (when appropriate) Create/find a suitable abstract representation of core ideas and information Examples: physics – equation representing process involved, chemistry – bond diagrams/potential energy surfaces, biology – diagram of pathway steps.	4 is a necessary component of 5, so 4 and 5 are often coded together. 4a could be a starting point in the problem-solving process. For example, making an observation and deciding it's relevant falls into 4a, which could then lead into formulating a question or problem to solve.	100	(theoretical physics) *(4 general and 4b, and portions also coded as 5 and 10)* Require writing down some equations, some models. You know, in many cases it's easy to write down the full problem with all its complexity in it, but then you just can't make any progress, and so you have to try to think about some approximations. And, so, that really translates into what do we think is the basic physics which is governing this particular process we're interested in modeling, and then how do we translate that into some sort of ... simplified mathematical description, which we can hope to sort of interrogate and understand.	(biology) *(also coded as 6)* Because we knew when they're self-fertile, they have oocytes, they have sperm, they have developing embryos. Which one of those things was the important thing?	(medicine) But that combined with some of the clinical features of his liver disease and overall presentation – I remember his fever was a prominent symptom he was experiencing in the context of his liver disease.	(earth science) *(4 and 4a. Beginning is also coded as 17, later part also coded as 18)* We'd look at lots of different bivariate plots of different elements until we arrived at a set of elements that we thought were most distinctive. In other words, there was enough of a. They varied enough among units that they could give you some dispersion. But they were also accurate enough and precise enough in the measurements that you could count on them. And it also, in doing that, it also brought to bear some information that we know based on what happens when rocks are weathered. Certain elements like the alkalis are easily disturbed, and so you don't want to base anything on the alkalis. So there are certain elements that you know don't work just sort of on a first principles chemistry background.
5) **What predictive framework?** Which potential predictive frameworks to use? (decide among possible predictive frameworks or create framework) This includes deciding on the appropriate level of mechanism and structure that the framework needs to embody to be most useful for the problem at hand.	We define predictive frameworks as "mental models of key features of the problem and the relationships between the features." Predictive frameworks involve some degree of simplification and approximation and an underlying level of mechanism that establishes the relationships between key features. The frameworks provide a structure of knowledge and facilitate the application of that knowledge to the problem at hand, allowing experts to make predictions for dependencies and observables and for interpretation of new information. The frameworks used evolve as additional information is obtained, with additional features being added or underlying assumptions modified. They help structure knowledge so that it can be stored and easily retrieved from long term memory when needed. Predictive frameworks are used at every step in the problem-solving process. Reflection on how well the predictive framework applies in the specific problem context is also an important, ongoing, decision during the solving process (captured in 23).	100	(mechanical engineering) [Responding to: "What were critical decisions?"] Deciding on a on a theoretical framework. On saying, Okay, I'm just going to pretend that this is flow through a pipe and I'm going to look at the resistance that that flow through an equivalent pipe would have and decide and use that as my criteria for deciding whether or not it was important.	(chemistry) So the idea is a platinum comes in and it breaks the carbon-hydrogen bond and then the other molecule comes in and then two carbons can bond and then -- come off, and then the catalyst can ---. And that was generally the accepted mechanism that multiple people have published as "okay, we think this is what's happening"	(ecology) *(also coded as 4 and leads into 6)* So now I had ... a theoretical framework sort of developing specifically around. Well, what are the mechanisms that drive the evolution of migration or the changes in migration, migratory behavior that are around interactions between genetic - genetically split environmental thresholds and environmental conditions? How might the cost benefit landscape be changing if you're a long distance migratory bird versus if you're an elevationally migrating elk? So sort of trying to formalize my thinking about what my hypotheses should be.	(medicine) All these things map onto heart failure, or syndrome of heart failure that you might have on your differential diagnosis and on your problem list.

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
6) **Narrow down problem.** How to narrow down the problem? Often involves formulating specific questions and hypotheses.	This is closely related to 3, but in a more specific context - it involves summarizing the general goal and translating it into more specific predictions. In some interview quotes, 3 and 6 are indistinguishable. 6 was sometimes also coded together with 4 and 5, because deciding on the important features and predictive framework was how the expert narrowed down their problem.	97	(biology) *(also coded as 5, and leads into 15)* So the logical hypothesis was that there's something about the chromatin structure of the locus that somehow changed the way the factor interacts with its site. Now that was a classical test of a hypothesis. Good old scientific method. If that's true, we should be able to look at that chromatin structure, map in fine resolution where things are.	(physics) If it changes in a particular way, then we know it must be a topological superconductor. If it changes in another way, it must not be a topological superconductor.	(medicine) *(also coded as 4 and 4a, and leads into 5 and 8)* One of the most important pieces is if she is menarchal, that is has started her periods. Where she is in her menstrual cycle because the causes of pain - and usually we're talking about lower abdominal pain slash pelvic pain. And we are interpreting that as I say in the context of the menstrual cycle and the causes of pain which might be an ovarian cyst, the types of cysts vary by where she is in the cycle and ...	(biology) *(also coded as 3 - as related to a decomposed component of the larger problem (11), and includes 4)* Well, then we thought, okay, different cells are expressing them differently. So they must have a functional significance that's relevant to each of those cell types. So then we just tried to understand what would be the functional relevance. For instance, one was predominant in a naïve t cell. One was predominant in a memory cell. So how would they contribute to the properties of those two cell types?
7) **Related problems?** What are related problems or work seen before, and what aspects of their solving process and solutions might be useful in the present context? (may involve reviewing literature and/or reflecting on experience).		97	(biology - industry) *(end also coded as 8)* What then happened is, we pulled out an older reference from the literature that suggested something specific about the configuration of the homology arms relative to the break itself. … We sort of looked at this and we went, "well, this is a different system, but we've kind of tried everything else."	(chemical engineering) *(also coded as 4a and leads into 8)* If I'm working for [company], and I'm drilling a deep water well in the Gulf of Mexico, I've got Borneo, Malaysia, um, west coast of Africa, Brazil…I've got analogs all over the world. And so part of this is just bringing that to bear to the problem, and knowing how to bring that to bear.	(physics) *(Slightly different context - related work as applies to a potential solution decided to avoid. Quote is related to 2, 8, and 26)* And that way you have to do six experiments and I knew that the systematics there were just overwhelming. People have tried it before and they could never say anything because you need to compare six… you take six big numbers and subtract them and look at all the differences right…any uncertainty just gets blown up.	
8) **Potential solutions?** What are potential solutions? (Based on experience and fit some criteria for solution to a general problem having key identified features.)	A "solution" can have a variety of forms. It can be a design, a diagnosis or treatment, a new scientific theory including an explanation of a phenomena, an experimental result answering some existing question, or a new method that allows existing problems to be solved. As the problem-solving process progresses, reflection on potential solutions (26) is ongoing.	100	(electrical engineering) *(also coded as 25, 26)* We did try a multimode approach instead of using single mode fiber to try and improve collection efficiency, go multimode…so instead of having like a 10 micron core size you could like 100 micron core size and you could collect a lot more energy from the return. The problem is there you have to make sure you excite all the modes in the fiber, or else you touch the fiber and you excite different modes and you see different signal at the detector	(biology) *(also coded as 3)* So if you basically have a large list of everything you have and you have three key criteria and you rank them on those three, then there is one specific cell type that popped up to the list [cell type] and we just settled on those. And also [other cell type], but that's a separate story.	(theoretical physics) *(also coded as 7 and 15a)* And just started speculating, about how we would do it and in the midst of that discussion came up with what sounded to us like a much more sensible approach--didn't really know whether it would work or not or whether it was mathematically sound, it required using a little bit of math and, and we weren't certain that it was sound, but it felt like it would be way better than what those guys were doing. And, and so we decided just to take a look at it. And because we had done some related calculations, we weren't starting with zero, we could repurpose stuff that we'd already invested in	

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
9) **Is problem solvable?** Is the problem plausibly solvable and is solution worth pursuing given the difficulties, constraints, risks, and uncertainties?	This decision is generally implicit in the fact that the expert picked the problem to describe in the interview (they had decided it was worth solving). It was less likely to be coded in interviews in medicine, or where the problem was given to the expert. Often when 9 was mentioned explicitly, it was in the context of deciding not to pursue an approach or describing the decision that a specific aspect of a problem or question is not solvable.	74	(biology) *(example of deciding not worth pursuing a particular approach)* And then I ended up just switching to a different strain that did it [crawling off the plate] less. Because it was just. It yeah. It was hard to really get them to kind of behave themselves. I suppose if really needed to rely on that very particular one I probably would have exhausted the possibilities a bit more.	(medicine) (*example of deciding not solvable*) Everyone in the room was crying. It was frankly horrible. But I felt and - basically what I said in that conversation was there are other therapies that we could try here but I recommend that we not do that. And I recommend that you do everything you can to maximally enjoy the time that she has left because even if we don't do that, even if you say no we want the next chemo and let's try the next chemo after that, even if you do that I'm pretty confident that it's not going to work.	(earth science) *(example of deciding plausibly solvable despite uncertainties)* The idea of going out to... looking at these ashes. Where that turned out to be one of the more impactful thing we did. Because in truth you know, only a few people care about calderas themselves. Is being willing to take a little bit of risk that this, whether this is going to play out or not, right. And going and collecting the ashes which was kind of a nuisance, because they were not easy to get to. I guess what I'm saying is that it was a little bit of a long shot. I was not sure that it was going to work.	
Plan Process for Solving						
10) **Approximations and simplifications.** What approximations or simplifications are appropriate? How to simplify the problem to make it easier to solve? Test possible simplification/approximations against established criteria.	Approximations and simplifications are also embedded in the predictive framework (5). 10 has a lower percentage than many decisions, because we only coded a statement as 10 if the expert explicitly described simplifications they made or approximations beyond those inherent in their predictive framework.	81	(theoretical physics) because there's five different theory papers out there that are…all have a different answer and it's not just solving polynomials. There's…these are hard problems and you have to make decisions at certain points of what terms of to drop and what terms to keep that are based on physics. There's no mathematically rigorous solution to many interesting problems in physics. So you have to decide what…what to keep and what to throw out.	(medicine) patient who has what looks like pulmonary congestion on chest x-ray and a history of smoking. These two things might not be truly, truly independent, but they're independent enough that it's a good approximation to say that they're independent.	(chemical engineering) *[Describing how to model oil flow in pipes if can't directly get sample of crude oil that will be extracted because of pressure issues]* So you do recombinations of those fluids in order to run the test. You synthetically create the crude in question—if you will. And that, it's not perfect, but it's a pretty good simulation.	(biology) *(also coded as 6 and 11)* To what extent can we approach this agnostically with strain improvement efforts, and to what extent can we, do we really need to understand what they are in order to engineer pathways to deal with them? So focusing on particular subsets. So things that were particularly abundant, or using a fractionation approach to try to identify fractionated subsets of those feedstocks that were more um toxic to the cells. Enabled us to focus the problem some.
11) **Decompose itno sub-problems.** How to decompose the problem into more tractable sub-problems? (Independently solvable pieces with their own sub-goals.)	The experts relatively seldom discussed decomposition explicitly, likely because they took it for granted as a fundamental automatic part of their problem-solving process. This was particularly true in medicine, where deciding how to decompose was rarely mentioned, although it is well established (and supported by our informal interviews) as being fundamental to how the medical diagnostic process is structured (e.g. thinking through organ systems). 11 could be considered a subset of 6, but, because of its importance in problem-solving we decided to list it as a separate decision. Decomposition often led to "iterations" in the problem-solving process. For example, in analyzing a decomposed sub-problem, the expert would return to 3, deciding on the goals for that sub problem.	68	(biology - industry) We have, uh, the cell. Which cell do we use? The gene. Which gene do we edit? Which part of that gene do we edit? How do we build the enzyme that is going to do the cutting? How do we put it into the cells? How do you provide the repair template to do the correction? How do we configure that repair template? And how do we read out that it worked?	(theoretical physics) And there were a couple of different aspects of our problem that I needed to explore. One is just the ability to represent the function and other one was the ability to represent a function that we didn't know exactly, because it had statistical uncertainties in it,	(ecology) So I analyze the bird data first on its own, rather than trying to smash all the taxonomic groups together because they seem really apples and oranges. And just did two kinds of analysis, one was just sort of across all of these cases, around the world.	

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
12) **Most difficult or uncertain areas?** Which are areas of particular difficulty and/or uncertainty in solving process? Could include deciding: a. What are acceptable levels of uncertainty with which to proceed at various stages?	This is often linked to 14, because the expert decides to prioritize (or prioritize ways to avoid) the areas of difficulty identified in 12.	90	(theoretical physics) because the thing we are analyzing in our ultimate final analysis comes from simulations, which are Monte Carlo simulations, which means that they have noise and I have statistical noise in them. And you need mathematical methods that aren't completely destroyed by having noise.	(medicine) *(also coded as 13, 18)* ... ultimately is always an HCG or pregnancy test, even if she is not able to acknowledge to us that she is sexually active. We may not have asked the question the right way, she may not trust us, there are a variety of reasons that she might not feel comfortable acknowledging sexual activity and missing a pregnancy-related acute problem is just so important that it's not that we disbelieve her, it's that we really have to have objective evidence to that effect.	(mechanical engineering - academia) *(also coded as 23)* One large challenge was the hand in my case didn't behave like a nice engineering system. ... In mechanical systems we think about systems with joints. Right, so if you think about your thumb, you have segments that are connected to each other by a joint. And you can build anything, you can have a nice engineering joint, and it kind of moves in one way, if it's a hinge like the hinge of a door, you know it moves in one direction. It has one degree of freedom we call it. ... Biologic joints ... can move in all kinds of ways. Um, 6 degrees of freedom in the real world.	(biology) *(also coded as 14 and 25)* I had three that I was able to clone and that had very robust phenotypes. [discussion of one she didn't pursue] Another one was a nucleoporin, and I actually started working on that first ... I ended up only being able to get so far ... at the time. In addition it made me want a protein that was different because it (the nucleoporin) was huge and very difficult to clone and make mutants in, and this was back in the day before we had quite the methods we have now. So then the only one that was left was completely novel. It wasn't a gene that had been identified, and it was very very small. So it was worth doing the next round of things cause I could clone it very easily.
13) **What info needed?** What information is needed to solve the problem? Could include: a. What will be sufficient to test and distinguish between potential solutions?	Ongoing reflection on knowledge (24) during the solving process will often lead to updated decisions about what information is needed. Also, 13 is often implied in 15.	100	(biology - industry) *(Also coded as 6, and 4 is implied)* We reasoned that there were two parameters that weren't optimal. How much zinc finger we put in, and what does the donor look like. We already knew how much donor to put in. We just didn't know what it needs to look like for optimal function.	(medicine) *(also coded as 8)* There are many other elements of the history that are important as well. I've mentioned the onset of the pain, the characteristics of the pain, if it were more a colicky type of pain we might - I mean there are other causes, things like pyelonephritis or a stone that can kind of present with lower quadrant pain as well. Urinary symptoms UTI, always in the differential. So you wanna get and hear about urinary symptoms, we want to hear about GI symptoms as well.	(mechanical engineering) (*also coded as 15 and 32, leading into 16*) So I just went and found [colleague] and said "Okay. So how fast is, what's the flow speed in through this" and and then I got this hour long discussion with [colleague] about all these factors. And then I got pointers to a couple of papers he had written that were these very dense things. But ... the only thing I was looking for as well. Actually, [colleague] pointed this out and said, "well, here is where while I am doing a whole bunch of other stuff I derive the relative flow speed through the slots." And I was like, okay, done. That's all I needed to know. And so, so now I have this number. And now I go and I use that in my. My pipe flow calculation.	(biology) (*end also coded as 14*) They had suggested a set of experiments that I didn't think were really going to get us there. So then it's a case of sitting down and saying "What would you need to see? What would you want to see in order to feel that you got some answer to that? And how then how could you most reasonably do that?" And then, then it's usually, do I have the tools to do that? Who do I know who might have the tools to do that?
14) **Priorities.** What to prioritize among many competing considerations? What to do first and how to obtain necessary resources? Considerations could include: What's most important? Most difficult? Addressing uncertainties? Easiest? Constraints (time, materials, etc.)? Cost? Optimization and trade-offs? Availability of resources? (facilities/materials, funding sources, personnel)	14 was often co-coded with other decisions, because deciding on priorities involves the weighting of a variety of factors. Decisions about resources were often coded with 3 (regarding criteria or constraints), while decisions about which approaches to try first or which parts of the problem to approach first were often coded with 15 (plan).	87	(physics) (*also coded as 33*) I said it's not quite going to work, but it's going to at least get us close, and we'll know how to improve it from there. If we try and just build the perfect experiment brand from scratch, I won't get tenure. It will be, you know, five years before we even start to take our first data, and then we may have missed something obvious and then we'll know nothing. *[Description of imperfect cooling system decided to start using.]*	(medicine) But at the same time there were - in a case like that where the diagnosis is very difficult to come by much of what you have to do is rule out all of the much much much more common things before you arrive at a point where you rule in the thing that's really going on.	(earth science - industry) *(also coded as 9 and 25)* when when you run into trouble drilling and the the drill doesn't make progress, you need to make decisions about do you keep going? The driller will tell you what their best estimate is as to how to continue making progress, and you have to. Here's where the money comes in. Well, it'll cost this much to continue or not, is it worth it? Or we're really stuck, and it's not going to continue under any circumstances. Or if we try again. Maybe we will.	

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
information. What is the specific plan for getting additional information? Includes: a. What are the general requirements of a problem-solving approach, and what general approach will they pursue? (often decided early in problem solving process as part of framing) b. How to obtain needed information? Then carry out those plans (b.2). (This could involve many discipline and problem-specific investigation possibilities such as: designing and conducting experiments, making observations, talking to experts, consulting the literature, doing calculations, building models, or using simulations.) c. What are achievable milestones, and what are metrics for evaluating progress? d. What are possible alternative outcomes and paths that may arise during problem solving process, both consistent with predictive framework and not, and what would be paths to	15a (general approach) is often decided early as part of framing the problem, but conceptually is still part of 15. 15b-2 (carry out plans) was represented in every interview in their description of what steps were taken. For 15 to happen, it is implicit that 13 must have happened as well, though we were usually able to distinguish them in the interviews. The experts continually reflected on their knowledge (24) and approach (25) and adjusted their plans accordingly.	100	(medicine) *(also coded as 8)* So first you rule out as I said before pneumonia, urinary tract infection, meningitis, diarrheal illness those sort of things. Then on the next level down you start ruling out things like babesiosis, endocarditis, Q fever, etcetera. Then on the next level down you start ruling out things like occult cancer, rheumatologic diseases like rheumatoid arthritis, neurologic diseases like multiple sclerosis. This case was made more complicated because as your descending down these layers, you're dealing now not just with a fever but also with all of the other things that attend to that.	(biology) *(example of 15b and b.2. End also coded as 21)* And so she *[postdoc]* developed this really nice system for measuring the time between nuclear envelope breakdown and reformation as the time as a proxy for measuring how long cells were spending in anaphase delayed by the checkpoint. And the stronger the checkpoint, the longer that delay would be. And so she had these little labeled nuclei in these embryos, and then treated them with nocadazole, something to kill their spindle. And she could see that the delay was not very long in a big cell, but as the cells got smaller and subdivided in embryogenesis, the delay got shorter and shorter, so there was this very clear time course in different cell stages.	(chemistry) *(also coded as 13, and reflection implied) [Responding to "what were critical decisions?"]* I would say the design of the original system - it was based on fundamental concepts that were solid, I would say, and then also we designed the system where we could make a series of molecules with ... So we could we could make a line. We had an axis. We had two axes. Yeah, so the design of the system was important.	(chemical engineering) *(15b and b.2. also coded as 6 and 11)* And then, then you run lots of tests. How long do I have when I…given a temperature gradient of X, um, how long do I have before these paraffins start dropping out on me. And, and uh how bad is it? And the other part of the problem is—if they do drop out, if I get a paraffin plug like this—how do I get rid of it? And again you test that. Or you try to build a model at the surface that allows you to test it.
Interpret Information and Choose Solutions						
16) **Calculations and data analysis.** What calculations and data analysis are needed? Then to carry those out.	The experts' plans (15) for analyses to interpret data would be coded as 16, regardless of if the decision was described before or after the data was collected. This decision also includes considering the limitations of the data. 16 and 17 usually came up explicitly in interviews only if/after the expert was asked how they arrived at conclusions. Without such prompting, the expert would typically describe the information they collected, and then what they interpreted or concluded from that information, without elaborating on how the data was analyzed. Thus 16 and/or 17 must have happened during this process, but we didn't have enough evidence to code for them. In medicine in particular, 16 and 17 were unlikely to be mentioned, because typically a doctor is provided with test results that are already analyzed by a lab or radiologist, so they don't have to make decisions themselves about how to analyze and represent the data.	81	(biology) *(also 15, with 18 implied, example of planning how to interpret data)* We did Western blots for proteins. We did Northern blots. And basically you try and use programs that quantitate. So you measure the intensity of the bands and you quantitate that, and you try to have some controls to quantitate for protein loading or for total RNA so that it's more meaningful. So that's how we did the quantitation. We also did quantitative PCR, ... with appropriate controls.	(earth science) *(also coded as 15 and 18)* Then re-dating the same thing over and over so you have some estimate of errors. So then you can actually do calculations of okay, this is the time gap of these two plus or minus x and you can actually do calculations that have errors on them. That allow you to be quantitative about things.	(electrical engineering) *(also 11 implied, and starts with 12)* . Had to worry about solar background. You had to first determine the bandpass you were going to work over and calculate how much solar radiation is in that bandpass that you are going to work under, so you had to go get those tables and do numerical integration to turn …determine how many nanowatts of power at 1550 …	(theoretical physics) *(leads into 19)* We'd have an idea, we'd write down sort of a—more or less detailed—mathematical description, and we'd then spend a week or two trying to solve it to see what it would tell us about the behavior.

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
17) **Represent and organize information.** What is the best way to represent and organize available information to provide clarity and insights? (usually this will involve specialized & technical representations related to key features of predictive framework)	This is a representation of the data to facilitate interpretation, not an abstracted model of features of the problem (which would be 4b or 22 depending on context). 17 was coded less often than others, for the reasons described above in 16, but was even less likely than 16 to be coded.	68	(biology) *(also coded as 16)* So then ... you have all the data and it tells you when each worm died. And you're able to build, they're called kaplin-meyer survival curves. They're just little like staircase looking curves that tell you how many individuals died on any given day. And then we can perform different statistics on them to figure out if one batch of worms died earlier or later than another.	(physics) When we started taking these images that I described of our system - we had these nice long string of atoms and we would take these pictures and then we would want to analyze something about how maybe this system was evolving in time or as a function of some parameter changing in the experiment. And at some point I realized that you could get so much information if you compressed this elongated system into a one dimensional image - like a row of pixels with some color and then made your vertical direction be time or whatever you were varying. And then you saw a picture that told you lots of things about what was going on whereas if you had just summed over the entire image and plotted versus time or had a bunch of different curves of what was going on at different times in the cloud, it was much harder to process.	(earth science - industry) (*also coded as 29*) Once I've made a description of all the rocks and then we got all the data back again. Then I had to write it up and I made my models by a series of cross section. So a series of two dimensional drawings and estimations. I did not put it into a three dimensional, three dimensions normally requires a computer program. [description of why she didn't make a 3D representation.] And a series of two dimensional cross sections was adequate for this job.	
18) **How believable is information?** Is information valid, reliable, and believable (includes recognizing potential biases)?	This applies to both previously existing and newly collected information. It focuses on the believability of the information, not on the applicability of the data to the problem (which is 4a). 18 is coded less than many other decisions, likely because an expert might not always encounter (or recall by the time of the interview) information of questionable validity. Validity would often be inherently considered in planning, as the final plan they constructed and described was designed to ensure the information they collected would be valid and interpretable. But believability was less likely to come up as a distinct decision after the information was collected.	77	(chemistry) *(also coded as 32)* Everyone was just like "are you sure this is your molecule? I don't believe you. This couldn't have happened."And so during all this time I'm trying to think of a way, and I'm also retesting a thousand times to be sure that this really happened. And it really happened.	(medicine) *(leads into 23 and 25 and implies 32)* And, in my very subjective sense, he seemed like he was being forthcoming and honest. Granted people can fool you, but he seemed like he was being forthcoming. So we had to reevaluate.	(biology) *(also coded as 15 and 19, and leads into 21*) So part of the controls come from just the statistics and the numbers that you're doing and being aware of that. But also, the question of do you count them all in the same day? Have you grown them all under the same conditions? There's a mutant and a wild-type. There are other [growth] conditions; it's making sure that everything is matched. And then a final step of saying, okay, I get this effect where maybe 70% of the cells are at the rim in the wild-type and it seems like only 45 in the mutant. How does that actually compare with things that I've seen in the literature that say that there's a defect in this. Am I way off? Should I be seeing 100% at the rim and zero? Does this fit in? I think that's another part of knowing what the assay you're working with is.	(mechanical engineering - academia) (*also coded as 15*) building sort of a ... mechanical measurement system that would allow us to collect the data that we wanted essentially. So there were some data collection hardware that we needed to purchase, that I needed to learn about, implement. So there's a hardware aspect. ... There's learning about implementing sensors, making sure that your sensors are calibrated, making sure that they're not drifting measurement. That happens over time.

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
19) **Compare to predictions.** As new information comes in, particularly from experiments or calculations, how does it compare with expected results (based on their predictive framework)?	Often coded with or leads directly into 21 or 22. Also often involves 4, implies 5, and sometimes leads into 23-26.	100	(chemical engineering) *(leads into 21)* And, and what was happening is as soon as we'd turn a well on, the pressures would just crater. And the only way that that happens if you're in a confined box—a box that's a heck of a lot smaller than you think it is.	(physics) *(also coded as 21, leads into 25)* What should this actually look like? Because I measured sound velocities in lots of other superconductors… not topological ones. We know from a measurement of, say, the resistance of this material as a function of temperature that the resistance should look like that. And this width here [points to curve], should be about 0.05 Kelvin. What [student] was looking at was more like 0.5 or more. And what that sound velocity should look like… is it should be a sharp drop. phase transition into the superconducting state, just like the resistance. And so I knew that while the physics we wanted was there somewhere, it was smeared out due to some kind of experimental problem still.	(medicine) *(leads into 22)* The problem is that that finding on exam might be an imperforate hymen if she reports she's never had a period, but if she reports she's having regular menstrual periods then that makes absolutely no sense that she would have a completely obstructing lesion. So a number of my patients have been seen by other clinicians and taken to the OR with a diagnosis of an imperforate hymen, when what they really have - you put together they're having an absent kidney, and the fact that they are having menstrual periods, they have a uterine duplication and a vaginal septum that has a unilateral obstruction.	(earth science) *(also coded as 31)* So the [calderas] we found are smaller, maybe a third the size of the ones at Yellowstone. But there was evidence for them. Some sketchy geologic evidence in the literature. When we went out and looked, I've worked on these things enough that I saw some clues, that I thought "yeah, I think there's other calderas out here too."
20) **Any significant anomalies?** If a result is different than expected, how should they follow up? (Requires first noticing the potential anomaly). Could involve deciding: a. Does potential anomaly fit within acceptable range of predictive framework(s) (given limitations of predictive framework and underlying assumptions and approximations)? b. Is potential anomaly an unusual statistical variation, or relevant data? Is it within acceptable levels of uncertainty?	20a is a specific implementation of 19, so it could be coded as both. Decision 20 was coded less frequently than some others, because the problem and solution described didn't always include any unexpected or unexplained outcomes that weren't accounted for in the expert's predictive framework. This could well have been different in the early stages of their problem solving, but may not have been reflected in our interviews because they had resolved such questions in completing the solution.	71	(biology) The incongruity was this: there were four binding sites. And in vitro, one bound the transcription factor super well. The other three didn't. Which makes sense because they really did not have sequences that were an exact match to what the transcription factor was supposed to bind. There was a weak [sequence]. But in vivo in cells, the protein-DNA and chromatin interaction data showed that the factors bind there just fine. And that made no freaking sense.	(medicine) And the delineation of the anatomy is really critically important. Often they're referred to me because they have unusual anomalies, and those anomalies can be quite complex. So those are patients in whom we would go through all of the steps that I've outlined, but would also really rely much more heavily on more specific imaging and in particular an MRI to delineate the anatomy	(theoretical physics) *(also coded as 12 and leads into 25)* it's just that the method we had originally imagined just didn't work - the Monte Carlo noise overwhelmed it. And I hadn't anticipated just how bad the noise problem was going to be, and so when you did a straightforward analysis using the method that worked for the S-quark your answer was overwhelmed by statistical noise.	
21) **Appropriate conclusions?** What are appropriate conclusions based on the data? (involves making conclusions and deciding if they're justified)	Both 19 and 21 involve reflecting on and interpreting new information, so sometimes they are coded together, but 21 is distinguished by involving reflection over a longer timescale than 19.	97	(medicine) *(also coded as 22, 26)* And after his Q fever serology came back positive, we consulted Infectious Disease to come by and made sure they concurred that when we told him that he did not HIV we were not in the wrong because obviously that would be an equally bad mistake as telling someone that they have HIV when they don't	(biology) And what I found is that even the young ones, when they didn't have self-sperm, and they weren't self-fertile, they succumbed and lived a shortened life span. So that experiment really helped us be like "okay, it's not their age." It has something to do with their germ line and their fertility.	(theoretical physics) *(also coded as 15, 24, 25, 26)* And if you apply our method to the toy model, here's the answer that comes out from our method. Look it agrees to within half a standard deviation with what our method gives and, and we did that. We also reanalyzed all of our stuff using other people's methods, showed that their methods overestimate the errors as far as we can tell, and, and show that our results were consistent with their methods—that that wasn't the point of difference between us and them.	

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
22) **What is the best solution?** Involves evaluating and refining candidate solutions throughout problem solving process. Not always narrowed down to a single solutio. May include deciding: a. Which of multiple candidate solutions are consistent with all available information and which can be rejected? (could be based on comparing data with predicted results) b. What refinements need to be made to candidate solutions?	A solution can take many forms (see note for 8). Often, but not always (with some field-specific variation), there is just one final candidate. The process of evaluating and refining candidate solutions leads to iteration of other decisions throughout the problem-solving process.	97	(medicine) *(also coded as 21)* And in and around the walls of the blood vessels they saw hiding this exceptionally rare thing called intravascular lymphoma. So they diagnosed him with lymphoma.	(ecology) *(example of a and b)* The preliminary answers are, they're partial. Like, for birds that winter at high latitudes, there's a consistent decline in migrating fraction. It's across all taxa, but most of the ones have been studied are in Europe. And almost every single study is pointing to climate change... the ice to be frozen and as melted, so the ducks can stay. Or there's more food in the winter and still easier for things to just stay. So that that was kind of the overwhelming picture. But what I'm seeing is the picture for a different group, for the terrestrial mammals that walk, the picture's really different. So they're all totally declining in migration too, but the reasons why are really different... From the cases I'm seeing it's all to do with land use change and hunting pressure and with fences and things like that. So, that reflects differences in their biology, I mean they're not just able to the fly over that stuff.	(biology) These isoforms fine tune the T cell responses, and contribute to the different properties of an activated, a naïve, and a memory cell. Memory development is an important aspect of vertebrate immunology. And the mice don't have these isoforms. They're only in human, and we found them in great apes. So they're a relatively recent evolution. And so we think that their function is to fine tune the T-cells that are most appropriate for the cell types.	(earth science) *(22, 26, and 29-implied but all in a general retrospective context, included as an example to highlight different nature of "solution" in different fields)* I think this is where geology is a little different from other things. Because the caldera story itself is a geologic history story. So that is basically you just publish it when you think your maps are good enough that you can do it. There's also the recognition that every map is a work in progress.
Reflect (ongoing)						
23) **Assumptions + simplifications appropraite?** Are previous decisions about simplifications and predictive frameworks still appropriate? a. Do the assumptions and simplifications made previously still look appropriate considering new information? (reflect on assumptions) b. Does predictive framework need to be modified? (Reflect on predictive framework.)	23 was coded less frequently than others because our coding of "reflection" required the expert to remember and relay their thinking process, in contrast to describing their actions which was the usual focus. For interviews where 10 wasn't described, 23 was also unlikely to be mentioned. Noticing an anomaly (20) often prompted reflection on predictive framework (23b). Sometimes reflection on solution (26) or approach (25) also required reflection on assumptions, so 23 often co-occurred with 25 and 26.	77	(medicine) *(beginning is also 20)* He had his hepatitis serologies – you know Hepatitis A, B, C, etcetera work – were all negative. That sort of didn't make a whole lot of sense to us. We have to then reevaluate whether some of our assumptions were not right.	(theoretical physics) At the same time, we then also could think about, okay that was a very simple model that we made, and we've made a lot of assumptions, approximations. Let's go back and sort of write down the more complete description of the problem, and then sort of systematically show where this simple model would come from.	(chemical engineering) *(also coded as 5 and 16)* Because I'm about to make a multi-billion dollar decision, and if I get that wrong I've blown a lot of money down the drain. And what do you have to do to get through that is a combination of building models to represent what this thing looks like based on the data that you have, testing the boundaries of these models. I mean these are often million-cell kind of models, and you're basically doing transmissivity at the boundary of each cell in the model. But how you model the, that homogeneity at the end of the day is critical.	(biology) *(example of 23 leading to new goals) (also coded as 10, 3, and 6; leads into 13 and 15)* The initial finding was [with] males around for a really long amount of time. But that's not really what happens in nature. Because in nature, the males are pretty rare for c. elegans hermaphrodites. ... So we weren't really looking at what really happens physiologically in nature and how they may have evolved to respond to that. So what we did was we developed an assay to ensure that mating happened, but that we could get it down to a really brief period of time.

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
24) **Additional knowledge needed?** Is additional knowledge/information needed? (Based on ongoing review of one's state of knowledge.) Could involve: a. Is solver's relevant knowledge sufficient? b. Is more information needed and if so, what? c. Does some information need to be checked? (e.g. need to repeat experiment or check a different source?)	Similar to 23, 24 was less likely to be coded because it required explicit discussion of the thinking process. 24, particularly 24c, is very closely related to 13 and 15. To code for 24, we required some explicit evidence of reflection, such as statements about re-thinking or deciding to collect additional information.	84	(theoretical physics) *(also coded as 23, 26, 32)* We did a new version of the entire calculation with this bigger collaboration. As part of that, having encountered [previous] criticism, we did much more elaborate testing of this particular method… Trying to address very specifically what people had criticized about it, and just trying to see whether there was merit in their criticism. That was where we were modeling our methods, but in in a controlled calculation, where we knew what the right answer was, so we could see whether our approximations gave the right answer within the error bars.	(medicine) And so by the time he got to [University] you know his [illness] presentation was significantly more complicated than it had been at the beginning and his condition continued to worsen. And he had now gotten not only a million-dollar infectious disease workup, but also a million-dollar rheumatology work up and a million-dollar neurologic workup. And all of it was completely unrevealing.	(electrical engineering) *(leads out of 25 and 26, also coded as 32; example 24a - deciding team's relevant knowledge <u>is</u> sufficient)* Also we had to make some compromises when we did the testing. We had to stop and go back in and implement a few more components into the building infrastructure before we could make those additional stories on the on the top of it. ... Fortunately, none of the limitations had to do with people's expertise. I've been on other projects and other teams where that was a limiter. ... We had a fairly competent team on my side as well as the people who are implementing it.	
25) **How well is solving approach working?** How well is the problem-solving approach working, and does it need to be modified, including do the goals need to be modified? (Reflect on strategy by evaluating progress toward solution)	Reflecting on goals and redefining the problem is included here, as is conducting test-case confirmations of solution approach. This decision often leads to iteration back to earlier decisions. It was often difficult to distinguish between reflection decisions, particularly 25 and 26 because in some cases the method (approach) was the solution to a problem or sub-problem. 25 and 26 also sometimes co-occur with 15 (plan), in the context of pre-planning how to test the method or solution described. This was coded as both plan and reflect, because the result of the planned test was explicitly to allow the expert to evaluate (reflect on) if the approach or solution was working.	94	(electrical engineering) *(also coded as 26 because the approach was the solution in this case)* No modulation there, just CW ... [discussion of data collection, calculations, and interpretation - coded as 16 and 19] ... We didn't do a timing gate, we just did one leg of the gate. Just to show that we could see the signal. But that approach [referring back to more details of design] is much more complex than the fiber approach. Now you have to line these two channels up and maintain alignment and if you ever mounted this thing on a helicopter... [details of potential problems with the approach/solution]	(biology - industry) we couldn't get more than let's say 2-3%. So then we had two questions. Is this just a fundamental limitation of the system? Or are we doing something wrong?	(medicine) And so when we saw that, we said alright well this completely changes how we're going to approach this man, because before we were thinking this man has hepatitis of unknown etiology, new onset HIV, no HIV risk factors so that's kind of weird.	(ecology) *(example of 25 leading to refinement of goals - new iteration of 3 and 6)* It was very quickly apparent that there were not a lot of data for taxa besides birds ... Wrestling with like, am I writing this paper just about birds where the vast majority of cases were, or am I also going to try to incorporate all these other miscellaneous bits and pieces? One case involving bats and a handful involving elk and deer and sheep, and, you know, one marine mammal case. And so like yesterday, I decided, I really better try to include all of them, because even if ... a bit piecemeal, there's something to be said for how much information is or isn't out there and whether there's any differences among groups in what's happening or why.

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
26) **How good is solution?** How adequate is the chosen solution? (Reflect on solution) Includes ongoing reflection on potential solutions, as well as final reflection after selecting preferred solution. Can include: a. Decide by exploring possible failure modes and limitations – "try to break" solution. b. Does it "make sense" and pass discipline-specific tests for solutions of this type of problem? c. Does it completely meet the goals/criteria?	In some fields like engineering, physical sciences, and medicine, there is likely to be an explicit reflective step after coming up with a final solution. In other fields, 26 may just come up in the context of ongoing reflection on potential solutions. The solution-reflection process could include physical tests; thought experiments and model comparison; considering alternative interpretations, possible overlooked confounding variables, limitations of investigation, and potential biases. This decision often leads to iteration back to earlier decisions. 26 is sometimes indistinguishable from 25, and both sometimes co-occur with 15 - see notes on 25 for explanations.	100	(medicine) *(also coded as 19, 20, 21)* But then as you get more data, you have to reevaluate, well maybe something is amiss here, maybe something's just not making sense. Again he had no HIV risk factors.	(electrical engineering) *(also coded as 22, 25)* My team did a lot of testing work to prove out that this thing does does work as we would wish it to be. And as with everything, we did find some scenarios that broke the tool and went back and said, Well, this particular thing is not working. Why might that be? And then there are things that we found that needed to be fixed and some things where we needed to make choices. And in the scenarios and then we made some compromises.	(biology - industry) (*example of 8 with 26a*) And dealing with that wasn't as straight forward for us, because the enzymes responsible for producing it (undesired byproduct) - normally we would just delete those. But they're critical for another aspect of the project, which is tolerating a lot of the inhibitors that are present in these complex cellulosic hydrolysates. So the enzymes that detoxify a lot of the poisons in these complex feedstocks are the same as the ones that actually produce this toxic intermediate in the [specific] pathway. So by knocking. By solving one problem we'd be creating another problem.	(physics) *(also coded as 16, 22, 25)* We make a prediction or solve a model and then, you scratch your head and try to understand does that result make sense or not by some other physical…simple physical thought process? Does that make sense or is that too large, too small? Or check this limit out. Does that go to make sense that if I reduce it to… And oftentimes you discover, if I take a limit where you know what the answer's supposed to look like and this thing doesn't produce that answer, then you know you're on the wrong track. So that's how we would often eliminate those approaches to try and solve those problems.
Implications and communications of results						
27) **Broader implications?** What are the broader implications of the results, including over what range of contexts does the solution apply? What outstanding problems in field might it solve? What novel predictions can it enable? How and why might this be interesting to a broader community?	This decision involves a very similar cognitive process to 1, but at a different part of the problem-solving process (1 is assuming new knowledge to be obtained, while 27 is in the context of reflecting on knowledge acquired). Given the structure of our interviews, it was not always clear which was being described. Often when experts described broader implications, it would be in the context of discussing their next steps to address the next related problem, thus 27 would lead into a new round of 1, 2, and 3. A subset of interviews had a specific 27 + 2 combination: The expert would describe their development of a new tool or theory, then move on to talking about what problem(s) they could solve using this tool. This 27 + 2 combination also involved 9 in that they were examining what current outstanding problems would now be tractable. 27 requires consideration of implications or impact beyond a single person – an expert's personal building of experience or intuition would fall under 31. 27 is presumably important in all fields, but was mentioned less frequently than many other decisions because its immediate relevance depended on: the scope of the project being described, the expert's specific role in the project, and the field (was rarely part of medical diagnosis problems).	65	(biology) And the therapeutic implications is that people are using T cells for immunotherapy. They're expanding them in vitro and then putting them back into patients. And they're looking at different sub-populations, and they have different manipulations. So T cell therapy is a form of immunotherapy now. So being aware of what isoforms the cells are expressing and how that might affect the function is relevant.	(physics) *(also coded as 28, 29)* Now, how do we build that into a convincing story, right? Because that on its own convinces people who do ultrasound for a living, because they know the details. So right now we have to turn this into a manuscript that's… It's a big result. This is an important result in the field of low temperature superconductors and quantum computer. So if you want to write it for a journal like Nature or something like this, you can't just start talking about sound velocities and things like this because, even in my field, nobody does this technique anymore, right? This is an old fashioned technique kind of up...we've updated a bunch of electronics and did some new things, but it's not something that anybody reading one of those journals is going to be familiar with at all. And that of course is probably the hardest thing for a student is to understand how to put their results in a context that a broad audience can understand.	(earth science) *(also coded as 28, 29)* And, this got a lot of press. Kind of embarrassing sometimes. Because it would go titles like "super-volcanoes will, you know, power… electric vehicles." So if you look up that, super volcanoes and electric vehicles. You'll see that it got, you know, widely picked up, partly because of the cleverness of our school's. You know I went to them and I said I think this might be a really good example of where some basic science that you know was not aimed at anything practical has turned out has been really kind of important. ... And so that was actually, you know that was pretty satisfying to me. To do something.	

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
28) **Audience for communication?** What is the audience for communication of work, and what are their important characteristics?	This was coded less often than others. Typical unelaborated mentions of "publish a paper" were not considered sufficient evidence of 28, although this likely implies consideration of suitable publications and corresponding audience for the work. Whether 28 was mentioned also depended on the scope of the project and the expert's specific role.	55	(chemical engineering) And we went around and we tried to sell that to a number of people, um, and um, you know it was interesting. Uh, people thought, "you know, that's a big deal, but there's no shortage of this right now. So, investing in something that would make this for a market that's already well-supplied…unless it could be made for a whole lot less," and the answer was, no it couldn't.	(physics) So there was an audience for this thing that was built in, because all the people building that accelerator and spending many millions of dollars to build it—many 10s of millions—all of them would be very interested. The people who are trying to do this calculation and the theorists who were trying to do the simulations would be interested. And, so, there was a community for it.	(medicine) *(also coded as 29, 32)* And then in describing it to the family, I need to have established trust first, hopefully doing that from the time I greet them, and as I do the exam, and as I explain to them the findings, and I say family because I'm dealing with kids and of course the patient herself. But I need to convey to them that right now it's my - I've done this a lot, been doing this for a lot of years, sometimes I will say that, although you'll look at me you realize that I've been around for a bit, I don't look as young as I used to [laughs], and they recognize that. But I would say to them that's it's my clinical judgement that this could be a torsion	
29) **Best way to present work?** What is the best way to present the work to have it understood and its correctness and importance appreciated? What makes a compelling story of the work?	Deciding how to present the work to various audiences often leads to iteration and refinement of other decisions. 29 was less likely to be mentioned in some interviews, because, similar to 27 and 28, its significance depended on the specific project, field, and role of the expert in the project being described.	68	(medicine) So in this instance, I explained to him a sort of shorter and less medically jargony version of what I explained to you a minute ago, and then said, based on all of this stuff that we just discussed my recommendation would be to get 6 months of chemotherapy, but having said that ultimately the choice is up to you.	(biology) *(also coded as 26)* So what helps me make that decision is presenting it, or preparing it in different ways. So presenting it an informal lab meetings, presenting it at formal meetings, and then also writing it up or preparing figures. So that really helps me kind of identify holes. ... Whenever you present it to people who have either heard it before or have never hear it put into kind of a story, you can figure out where people get hung up on things or where their big questions are, and that helps you take a step back and see how other people view it and what they think are remaining questions or problems.	(chemistry) Trying to sell the paper and tell the story in the end. Because it's seen almost as a negative result, and people aren't [inaudible]. Like, oh, "we thought you were working on platinum catalysts. We'd be more interested if it was platinum catalyzed." And a lot of people wouldn't have taken the time to do those experiments. One they notice that it might not be platinum catalyzed, they might have given up and moved on. And not gone through with showing that clearly it was not platinum catalyzed. But I thought that was important.	
Non-Decision Themes: Ongoing Knowledge and Skill Development	**These are additional themes that frequently came up in the interviews but are not specific problem-solving decisions. These do involve different sorts of decisions in practice, but we did not explore those in this work.**					
(30) **Stay up to date in field. Could include:** a. Review literature, which does involve making decisoins about which is important. b. Learn relevant new knowledge (ideas and technology, from literature, conferences, colleagues, etc.)	This is often co-coded along with 7 or 4a	84	(biology) I'm a big believer in never using three months in the lab to save an hour on PubMed.	(earth science) *(also coded as 4a, 6, 7, and 15, with 14 implied)* The initial thing that we did was just reconnaissance. Got the literature together. Found the places where there were relatively recent dates. Tried to put together the story and places where we thought we should go look.	(earth science - industry) *(also coded as 32)* I guess the same thing is when you're doing academic research: read as much as you can and ask as many people as you can about what's already known or thought about the area and ask other people for help.	

Decision	Notes/Comments	% of inter	Example 1	Example 2	Example 3	Example 4 (if needed)
(31) **Intuition and experience.** Acquiring experience and associated intuition to improve problem solving.		77	(biology) *(also coded as 30)* [when asked about differences between expert and trainee] I think that I do a better job, or have more experience finding or seeking out literature pertaining to something I'm seeing, or a technique, etc. And then, unfortunately it's just experience, trying to then say "okay, this has been done before, or this hasn't been done before, or is this an important thing?" ... So I think being able to more efficiently find things in the established literature pertaining to a technique or to what is known about some biological process. And then also combined with okay, what is the story I'm trying to tell.	(medicine) *(leads into 7, 24, and 26)* And so sometimes we'll engage in that discussion, well I think there's a 75% chance that it's torsed. But it's usually on the basis of how well things fit together. How well the clinical history, how well the exam, how well the imaging, fits with my clinical experience. And I've had a lot of clinical experience with torsion. And a lot of clinical experience with torsion in teens. So that's what I'll put together, the past cases, the cases that I've been wrong. What did I learn from that case?	(mechanical engineering) *(also coded as 26, because he's referring to his solution)* Since I had the physical things in front of me I could. I was just sort of holding it and just kind of imagining. Well, you know, I've seen pieces of steel before and this is... Typically If they are in these different configurations... And so it's this kind of intuitive thing.	
(32) **Interpersonal, teamwork.** Includes navigating collaborations, team management, patient interactions, communication skills, etc., particularly as how these apply to the context of the various problem-solving processes.	This was mentioned in every interview, and teamwork and communication were often highlighted as critically important parts of the success of the expert.	100	(biology - industry) Absolutely for me, by far. What was really enabling was the collaboration. So this has less to do with algorithm of decision making, but being able to step out of your own narrow head. And continuously, it. Daily bounce, bounce back and forth. It was completely enabling.	(chemical engineering) most of the examples that quickly come to mind in my case are inevitably team-related things. They're not individual, I'm trying to solve a specific engineering problem in this particular context. I'm trying to solve something bigger than that, and I may be leading the team, I may be a member of the team, but the problem is bigger than me by itself.	(theoretical physics) And so we joined forces with this much larger group and are starting to redo the whole calculation with much better, much more computer time and more accurate simulations	(medicine) I also recognize that all decisions about medical care ultimately should be made by the patient. And so I view my role not as making the decision but as explaining the evidence, making a recommendation when appropriate, and then asking the patient to make a decision.
(33) **Efficiency**. Time management including learning to complete certain common tasks efficiently and accurately.	This was mentioned less frequently than others, but often enough to include as a theme.	32	(physics) So you're trying to chart, an efficient path to figuring out just how good your insight is.	(biology - industry) *(also coded as 3, 6, and 32)* I think that I and other scientists have a tendency to get really excited about the science and understanding. And ultimately, that can be critical for reaching your goals, but achieving those final targets is really the main driver. So when understanding isn't essential, sometimes my role is to reign people in.	(chemistry) *(also coded as 15, 31, and 18 - implied)* I think thinking back to myself as a graduate student, I definitely did a lot of ... not the smartest experiments. You want to be rigorous, but like as a graduate student, for me, if something didn't work - sometimes you don't know if it's because it's You or if it's the reaction. And so you kind have to make sure, right? So there's a lot of that going back and forth, I would say, that's part of the learning process.	
(34) **Attitude**. Motivation and attitude to the task. Factors such as interest, perseverance, dealing with stress, confidence in decisions, etc.		68	(physics) *(also coded as 14)* We sort of got so excited about the new information we were getting looking from the side that we for awhile didn't even bother to pay much attention to this other channel for getting information.	(biology) I have had just an almost emotional interest in gene regulation since I was a high school student. If I could trace it in some meaningful way to something even vaguely intellectually.	(biology - industry) *(also coded as 32)* I like to try to get people motivated and excited by the work that they're doing so that they can really be the ones to drive it. I think that when people are the intellectual leaders of their own work that enables to be much more productive and to bring insights that I couldn't bring to the project. So the extent possible I like other people to be driving some of that.	(mechanical engineering - academia) Being comfortable with maybe not knowing certain things. So there's a comfort level. … Practice, familiarity, confidence. Being okay with failure. Being able to learn from your mistakes.

Supplemental Data Set: Transcripts of Expert Interviews

Contents:

Molecular biology faculty + industry

A: Okay, so, um. What I'd like you to do today is think about a problem that you have solved or project you completed. You might have to go back to thinking about something at [company], if that's when you were actually solving a science problem, but if you've been, if you've solved something more recently, that's fine, or great. And um particularly think about a problem where you can think about the detailed decisions you made when you were solving the problem. and then what I'm going to have you do is walk me through everything you did. Um, so all the steps you went through as you were solving the problem, what goals you were trying to achieve, what you did, what decisions you made.

B: That sounds great. But this will, this will get pretty technical pretty fast.

A: That's fine.

B: You personally are obviously more than okay with it because we're of the exact same background. But your colleagues won't understand 2 to 3 quarters of what I'm about to say.

A: Um, so that's fine. So we have. We're looking at this from the lense of, we know that the details matter, but when we look at it, we can also pick out the general trends. So I can look at it and understand the details, and then other people can look at it and look at my notes on it and see, oh yes there he was doing this sort of decision, there he was doing this sort of decision. So I think that it's fine that it gets technical.

B: So, okay. The first. I think it would make sense to parse the types of problems I solve into scientific inquiry, which is essentially an investigation of the unknown. And tool building, which is essentially, um, you know, gathering the right components to obtain a particular kind of outcome. And they're different in the sense that, um, and I've actually never thought about. Um. I think that tool building is slightly more um, algorithmical. And slightly more iterative. And sort of one step at a time, than open ended inquiry. Because open ended inquiry. And maybe we should start with this first. Open ended inquiry, um, … you… worlds where there are multiple directions. And you know frankly certainly in my scientific career, you almost go with your gut

A: Ah

B: And the gut is kind of hard to make algorithmic

A: Right

B: So let's do a tool building one first

A: Ok

B: And um, and um, and then let's do a basic discovery one

A: Sounds great

B: For tool building, I think the simplest to use, because it's published, it's relevant, and I think we can learn a lot from this. Is getting gene editing to work. So there's a paper, [paper]. And um, the ultimate goal was to figure out a way to get efficient targeted genetic engineering of a native human gene. That

was the end. That was sort of the end goal at the very end of the day. And um, when we started, um, it was, there was a publication. So by the way, so needless to say, the very first, um, and I'm sure every single one you interview will say this. I'm a big believer in never using three months in the lab to save an hour on PubMed.

A: (laughs)

B: I mean obviously the very very first step is you try to deeply understand what are the giants whose shoulders you're standing on. And one of the interesting things about that process is you tend to be biased by the methods and findings. Um, somebody tried this and this failed. Or this has been conclusively investigated and the answer is mmmm. And one of the advantages of tool building vs. discovery is the following. Tool building, by definition involves iteration

A: Uh-huh

B: And involves absolutely a certain amount of heuristics. You literally try random things and see what sticks

A: Huh

B: Which sounds unbelievably, um, sort of, um, unexpected I suppose. I mean, what what happened to common sense. And they're not really random things, but they basically attempt to attempt the question of whether the precedent you're standing on has actually been truly cor----.

A: Uh-huh

B: So in our case, what we knew and what had been published, is that there is only one kind of enzyme that did gene editing, these zinc finger nucleases. And they were used successfully in two settings. In a fruit fly and in a reporter system in human cells. And the efficiency was just super low

A: Mhm

B: And further more in mammalian cells, this only worked at a reporter, at a reporter gene instead of at a native gene, which was of course what we set out to do. So I mean, unequivocally and binarily, the dominant principle of any tool building is divide and conquer

A: Ok

B: Um, you try to, You fragment the challenge into as many components as is meaningful without sort of fragmenting them meaninglessly. And you attempt to improve the components separately under the assumption. And this is a key assumption you're making. That optimization of the individual components will ultimately then, you know, produce an improved overall whole.

A: Uh-huh

B: And that is. But the good news is that is something you can test. So here we essentially had, uh, let me just run down the list of variables.

A: Ha

B: We have, uh, the cell. Which cell do we use? The gene. Which gene do we edit? Which part of that gene do we edit?

A: Mhm

B: How do we build the enzyme that is going to do the cutting? How do we put it into the cells? How do you provide the repair template to do the correction? How do we configure that repair template? And how do we read out that it worked?

A: Mhmm

B: So we've just compiled a list of variables. And we're sort of at the proverbial cross-roads of having to make, having to make sort of sometimes informed and sometimes slightly uninformed decision about all of those.

A: Hmhm

B: So it is certainly the case, and this is pretty much one of my sort of dominant, dominant modes as a tool builder. And I'm sure pretty much everybody else is more or less like this. Is the thing that you focus on first and foremost is you focus on the reliability of the readout.

A: Mmm

B: So whatever you're doing, if you cannot reliably and reproducibly with good sensitivity and good specificity measure what the answer to your question is, then you shouldn't be asking questions (laughs)

A: Haha

B: If you're asking somebody a yes-no question but you can't hear what they're saying, well, you have to switch your mode of communication

A: Right

B: So in our particular setting, it was very very apparent early on that tools to read out gene modification at conventional genes were simply enough were simply not sensitive enough and they were not scalable enough

A: Interesting.

B: So my colleague [name] made the very wise decision that he will also use a reporter system. And the advantage of using a reporter is, um, you have a standardized piece of equipment, in this case a FACS machine, that is robust, and it will run an assay at the same robustness level that it will run 96. By the way, you need to ask yourself what is the scale at which you're doing this.

A: Right

B: Do you need to take 1000 measurements? do you need to take 10 measurements?

A: Right

B: And that is in turn a function of well how many variables are you going to permute? And we knew the number of variables we could meaningfully compute was in the low hundreds

A: Uhuh

B: So a conventional FACS machine which can do 96 in an hour was compatible with our timeframe. So, there's also how much time do you have to do this? I mean, Do you have a year? We had a couple months.

A: Right

B: So you have an assay. Do you have a piece of hardware that can do this? Yes. Can it do enough of those assays in the amount of time you have? Yes. Okay. What else do you want to know about the assay. Well, this is literally step zero. Is what's the baseline?

A: Uh-huh

B: How much signal do you get when you don't do anything. Second, at the other end of the distribution, when it works spectacularly, what will the signal look like? This is what it's going to look like. And in our case, the dynamic range of the instrument was sufficiently robust to for example tell the difference between 1% and 5%

A: Ok

B: And then between 5% and 20%. And that was important to us because 20% was where we needed to get to, and about .5% was where we started. So that was good. We knew that the machine will sensitively measure the impact on the system that we are trying to have. Then all the classical tools of experimental science. Uh, how robust is the assay? Well, what are, what do the technical replicates look like? And these by the way, I should also say uh that if you look at any assay development, and you look at specificity, sensitivity, linearity, loq, lod, I mean, there are volumes written about this.

A: Uh-huh

B: For any given assay, what are the metrics, um, that. And for us, um, certainly technical reproducibility was important, in other words if we're measuring the same sample twice. We would get variability within, well let's say, um 10% of the absolutely value of the signal. So could we measure 20% +/- 2%

A: Hmm

B: Effectively? Yes. Um, the other huge question is well how much biological noise is there in the system? What do biological replicates look like?

A: Right

B: What do the biological quadruplicates look like? And it rapidly emerged for example that biological replicates don't look tight.

A: Huh

B: And So what you then do is you say how many biological replicates do you need to do? Until the bounce in the signal becomes, essentially, until. This is the decision matrix. Here is the untreated, here is the treated. Here are the error bars between biological replicates. So the error bars obviously overlap between done and undone. That's not acceptable.

A: Right

B: Let's do it four times. It starts to look like this. Let's do it six times, it starts to look like this. So you basically want to power the experiment to sensitively detect. So we picked a reporter. Um. In terms of another guiding feature, for sure, is just operational feasibility. Can you do this?

A: mHmm

B: So what were we doing? We were basically putting DNA into cells. We did not want that to be a limiting factor. So our decision matrix for cells was a very simple one.

A: Ah

B: These needed to be cells that we could grow. Because we needed a lot of them. If you can't grow them, they're not our cell type. And these needed to be cells that we can transfect efficiently.

A: Mhmm

B: And that narrowed down the matrix super fast. And we needed to FACS them. So if you basically have a large list of everything you have and you have three key criteria and you rank them on those three, then there is one specific cell type that popped up to the list [cell type]'s and we just settled on those. And also [other cell type]'s, but that's a separate story. Um. Okay. Then we needed to decide which gene. Well, for the native gene, we knew which gene we were going to use. For the reporter gene, which was what we started with.

A: Uh-huh

B: We needed to pick the one that gave us the best signal. And um, we basically at that point, heh, we tried the one that we currently had.

A: Uh-huh, laughs

B: So you know, and sometimes just availability, so what you have on the shelf is a surprising contributor to your brilliant scientific insight

A: Right (laughs)

B:Why did you pick GFP? Well, we had it.

A: Yeah (laughs)

B: So I think the excellence is the enemy of the good in these kinds of these things. I mean, had we picked mCherry, I don't even know if it even existed back then, would we have gotten slightly better signal? Maybe?

A: Uh-huh

B: Okay. next, we needed to pick and this is sort of where it got super fun. Uh, We needed to pick, um, the zinc finger.

A: Uh-huh.

B: So there there was a giant sort of, giant wormhole. Because … thousands of different zinc fingers existed. We didn't know which one. So. What we decided to do is first we tried to simplify the system. You can use as few unknown components as you could. So a zinc finger nuclease is actually a heterodimer of two. We didn't want to have to fight with that. We had one zinc finger that we knew worked in a bunch of other assays

A: Okay

B: So it looked pretty well behaved. So we built a system we only needed to use that. And so again the logic there was, "since we don't know what works, and we need two of them. So we're gonna have unknown one and unknown 2, and if they fail and we don't know because of which one. Let's not do that.

A: Huh

B: Let us instead, construct the system where we minimize the number of the unknowns.

A: Mhmm

B: Now. We've settled on the cells, we've settled on the assay, we've settled on the zinc fingers. And then the fun began. So where the fun began, and this is the iterative.

A: Uh-huh

B: We basically had two variables. How much of the zinc finger to put in, and how to configure the repair construct, and how much of it to put in.

A: Uh-huh

B: Obviously this is the old school way, which is unbelievably common in experimental science. Is you hold one variable constant and you compl, and you extensively titrate the other.

A: Uh-huh

B: This is the foundation of all experimentation. In this case, we basically put in as much of the zinc finger as we could, and we took a particular configuration of the repair template, and we just basically did a very broad curve. At the lowest extreme, nothing happened. At the highest extreme, the cells died.

A: Okay (laughs)

B: So somewhere between that, where the cells wouldn't die and we saw something, was the sweet spot. And when we did that, so we went from a baseline signal of let's say .5% to, it doesn't really matter

how much of this repair template we put in, we couldn't get more than let's say 2-3%. So then we had two questions. Is this just a fundamental limitation of the system? Or are we doing something wrong?

A: Mhmm

B: So at that point, we had no option to give up. We had to get this to work!

A: (laughs)

B: So I suppose this is one setting where industry inquiry differs from, um academic inquiry. In academia, you go, well, that is not working, let's try something else. In industry, you just pursue.

A: Ah

B: It's boring, but. So. We reasoned that there were two parameters that weren't optimal. How much zinc finger we put in, and what does the donor look like.

A: Ah

B: We already knew how much donor to put in. We just didn't know what it needs to look like for optimal function

A: Ok

B: So we held the amount of donor steady at the optimal determined touchpoint. And we titrated the zinc finger.

A: Uh-huh

B: At the highest dose, the cell died, at the lowest dose, nothing happened. At the place where the zinc finger. We're still at 2%.

A: Right

B: And at that point we realized, that it is probably the way the donor looks. Like how long it is. Is the remaining variable. And so at that point, the heuristics start to come in.

A: Okay

B: You start to, you literally try things that. I mean that are biologically sensible. How long, how long is the left homology arm? How long is the right homology arm? Where does the right homology arm start and end? Where does the left homology arm start and end? Now clearly you drive some of this based on literature. But here's an example where… you know precedent in the field said that, you know conventional gene targeting required homology arms of 50kb. That was an. That was not an option for what we were trying to do.

A: Right

B: That was just incompatible with our experimental goals. And I said no way. We are limited by X. So mother nature imposed a fundamental constraint on us. So we said, fine. Within those constraints, let's

do the best we can. Mmm, mmmm (hand gestures). Things started to creep up. But they were still not at the 20. And then I suppose you know, to be honest with you, we sort of just sat there staring at this thing

A: (laughs)

B: And you know, just objectively, what then happened is, we pulled out an older reference from the literature that suggested something specific about the configuration

A: Uh-huh

B: of the homology arms relative to the break itself. And um, [Name] e and I. This was with [collaborator name]. We sort of looked at this and we went, “well, this is a different system, but we’ve kind of tried everything else. “

A: Uh-huh.

B: So typically at least in my world, when your back is to the wall, you sort of try for the things that make somewhat sense. I mean, we’re not going to add powdered sugar, but

A: Right (laugh)

B: But things that. And that’s what made the difference. It was changing the configuration of the homology arms relative to the break that got us to the 20%. So to recap, you. So sort of in a toolbuilding method. You start by convincing yourself that ---- the readout you’re going to be using is, has all the desired linearity, specificity, sensitivity, loq, lod, all of those good things. Then you ask, “well, what’s the setting you’re going to do this in?”

A: Mhmm

B: You have a set of cells, locus, construct, this this this. You try to minimize the number, the amounts of the unknowns. And you try to not create problems for yourself. So if you need to put DNA into cells, don’t work with cells that a) don’t’ grow, and b) don’t pick up DNA.

A: Right

B: Well, what cells do we currently have that grow and pick up DNA? these. Okay, let’s use them.

A: Right

B: Then once sort of you’ve made those relatively simple decisions, and you’ve come to the point where you have to iteratively and sometimes heuristically get to the answer, you again you try to sort of at least simplify to the point where you anchor one thing and you change something else completely. Once you get to an optimum point, you anchor that thing and change the other thing as much as you can.

A: Mhmm

B: You’re climbing. It looks a little bit like. It’s sort of like rock climbing in a sense

A: (haha)

B: You're stuck to a wall, and you have all your. This is what you have and you need to get up to the next step. So you take one limb, and you and it goes up, and you find something that you can truly hold onto. Snap. Okay, we're holding onto that. Now we get to move the other limb, and the second …

A: Uh-huh

B: So that's a te… of. That's a tool building. That's a generic sort of tool building …

A: Uh-huh. So what would you say were the critical decisions that you made during that? Of all the decisions (laughs)

B: Okay. Uh. Absolutely the decision to use a reporter system. So getting a system that would give us the assay that we would need.

A: Uh-huh

B: Two. Simplifying as much as we humanly could the sort of the way the system was put together. So using just one zinc finger instead of two. Three. Um. Not giving up.

A: Hmm

B: In the sense that just really being. But to be clear, this was a decision that was imposed on us.

A: Right

B: The company said "this must work." Now we were excited to get this to work, but

A: Right

B: You know. Um. … I'd say that those are the three. Oh. Sorry, last thing. Absolutely for me, by far. What was really enabling was the collaboration

A: Ah

B: So this has less to do with algorithm of decision making, but being able to step out of your own narrow head

A: Uh-huh

B: And continuously, it. Daily bounce, bounce back and forth. It was completely enabling

A: Huh

B: his is what made it. If we didn't have an environment in which we could just sort of. You know we joked we were Lenin, McCartney. We joked who's Lenin who's McCartney.

A: Haha

B: Um, but there was absolutely that component where there's sort of a 1+1=7.

A: Uh-huh. … And how did you determine that you'd gotten it good enough? How did you decide that "alright, we did it."

B: Mmm. We knew that in a real world setting, in order to make a difference. Because…

A: Uh-huh

B: We would need to obtain a certain number. A certain … And we basically exceeded that number.

A: Okay

B: So there was an environment pre-specificied metric.

A: Um, and so what were the main challenges that you encountered?

B: (cough) … About halfway through this it just wasn't working. … Um, … So we basically had to start scraping through. Sort of reaching to the bottom of the barrel in terms of ideas. Um. .. The reproducibility. Like on one day we would do this and get a certain kind of number, and on the second day we would do… And honestly it came down to the habituating yourself with the experimental system

A: Uh-huh

B: It's almost going into ski or bike. Like, the wheel is wobbly on the first few tries, but then after you practice enough times and you develop a steady ride.

A: Right

B: So literally honestly on some level it came down to just a familiarity with how the system works and how to get it to behave.

A: Okay. Um…

B: So that was a um, a tool building.

A: Okay, yeah.

B: A shorter version of it for basic discovery. Um, so I'm going to use something I did as a postdoc, because I think it's probably the simplest scenario. There's a paper [paper]. And um, the biological question before me was this, um. There's a gene responsive to a transcription factor, and the transcription factor is, um… has four binding sites in the target promoter. And the question is why. Why not one? And so cutting to the chase, the conclusion of the paper is there's a really fascinating mechanism of attenuating. It's basically a negative feedback loop, believe it or not. That the system has set up to do. So this transcription factor, it regulates its own gene. So the gene for that transcription factor has four binding sites for itself.

A: Ah-huh

B: You imagine there'd be a completely runaway process, where the more, the more of the transcription factor you have, the more of it you make, because it turns itself on. So that turns out to be not true

because three of the four biding sites in fact depend on a particular organization of chromatin on the promoter.

A: Ah

B: And one of the things the transcription factor does when it binds, is it remodels chromatin

A: Ah

B: So more transcription factor remodels chromatin in a way where the transcription factor evicts itself

A: Ah, interesting

B: But I didn't know that.

A: Right

B: This was discovered. So what did I know? I knew there were 4 binding sites. And, um. I knew. Um, that their sequences were somewhat different. Uh, and that's pretty much all I knew. So I think, for me, in basic discovery, I mean at the end of the day, yes, yes, people will say "oh, then I had this brilliant hypothesis that this is how this works." I've had really really few experiences like this in my life where I would ab-inicio say "ah-hah!" I'm not Francis Crick, who invented, as we all know Francis Crick *invented* tRNA

A: (laughs)

B: It's a well-known fact. He wrote a letter that said "tRNA must exist."

A: Ah

B: Or you know Sidney Brenner, same deal with mRNA. I'm not that. My approach near always is, you look at a system, in my case that was this. And you ask, what kinds of assays do we have now

A: Uh-huh

B: To explore how a system of this type works?

A: Uh-huh

B: Now you obviously don't want to do random crap.

A: Right

B: And a foundational tool in my field is sort of reverse genetics, so you take things away and you see what happens. So I certainly did that. So I um, I took, um. But then the other thing to say before I continue with this is to say there are just fundamental ways to look at, sort of the. I suppose the molecular architecture of this thing in living cells. So you can map chromatin structure, you can map protein-DNA occupancy. I mean, honestly, in other words I did the simple things first.

A: Uh-huh

B: So I removed one element, and then the other element. So those are very simple to do. And I made certain observations about changes in behavior that didn't really quite tell me what was going on.

A: Uh-huh

B: And then I. Again, to be clear. I uh, um. I then mapped chromatin and protein DNA interactions. And I observed.

A: Ok

B: In other words, I didn't do this being driven by a notion of how the system was working.

A: Right

B: I just used existing assays. Essentially the way I think about this as a scientist, you sort of try to map the shape of the. How big is the elephant?

A: Huh

B: I know it's not just a trunk or just like a rope or just like a barrel. But how many different kinds of parts do we have? (gesturing)

A: Uh-huh

B: Sort of the (gesturing) In other words, I don't know what the elephant looks like, but at least it seems to have 7 different kinds of parts. I don't understand how they're put together. And something I discovered right off the bat, which was just deeply striking. And there was just such an incongruity between those two finding, that that basically. So the incongruity between the data is what produced the, the ultimate discovery.

A: Ok

B: The incongruity was this: there were four binding sites. And in vitro, one bound the transcription factor super well. The other three didn't

A: Ok

B: Which makes sense because they really did not have sequences that were an exact match to what the transcription factor was supposed to bind. There was a weak. But in vivo in cells, the protein-DNA and chromatin interaction data showed that the factors bind there just fine.

A: Ok

B: And that made no freaking sense. There was only one hypothesis, and the hypothesis was: that paradoxically there was something about. So what's different about test-tube and cell? Chromatin!

A: Right

B: So the logical hypothesis was that there's something about the chromatin structure of the locus.

A: Uh-huh

B: That somehow changed the way the factor interacts with its site. Now that was a classical test of a hypothesis. Good old scientific method. If that's true, we should be able to look at that chromatin structure, map in fine resolution where things are. And when I did that, again using established methods. You know it very rapidly became apparent that these binding sites are very non-uniformly distributed within chromatin

A: Huh

B: Such that, as more transcription factor, the transcription factor activates its own gene. Uh-huh. Um, and one site is preferentially occupied at all times, but the other three, their occupancy in turn remarkably … is dependent on a relatively unperturbed chromatin structure.

A: Huh

B: So the more. And of course when it bound. So. Which was, I don't want to say paradox. It was like a kind of a deep finding. Um, so somehow this transcription factor establishes a cohabitation with a nucleosome. As it is activated, and tries to turn on transcription, … one of the protein-DNA interaction sites just continues to function, producing steady state. But the other three. The weird ones. As the transcription factor turns itself on and starts to activate transcription, it also changes the nucleosomes, and paradoxically the transcription factor falls off.

A: Ah

B: So to recap. I was interested in a problem of how. Why this gene. No, so why I was I interested in the problem? I just found it kind of cool, auto-regulatory systems. Wow.

A: (laughs)

B: How does this regulate --- machine work. Ok. Well, what do we know? We know there are basically four intervention points. They just look really weird. Uh, well, let's do an established assay. Binding in vitro. Ok (shrugs). Well the three others look ugly. Um, and. And then you look at them in vivo. And they are all bound. … That makes… in other words, the first experiments were not hypothesis driven.

A: Right

B: They were mapping out the terrain using established assays.

A: Uh-huh

B: So, start with a curiosity. Map out the terrain with no hypothesis. Just can we learn more? See something that makes no sense. That immediately gets you to a hypothesis. The hypothesis can be tested with an established assay. Do the established assay. Bam, get to the result.

A: Uh-huh

B: That's my story and I'm sticking to it.

A: (laughs) Um, so. In both of your cases, how did you end up deciding to work on that problem in the first place?

B: Two completely different avenues. Um. The basic science is easier to answer.

A: Ok

B: Um, ssss ... I have had just an almost emotional interest in gene regulation since I was a high school student. If I could trace it in some meaningful way to something even vaguely intellectually. Converting emotions to intellect. … I think I was drawn to DNA because of its visual. Just almost visual beauty and simplicity.

A: Huh

B: And I was just amazed by the notion that this sort of uniform and beautiful thing could beget so many different kinds of outcomes. Here's this structurally stereotypical thing. And there's this sequence inside, and the sequence is brought to life by these proteins. I thought that that was just a really interesting challenge. Um, intellectually. Like how is the code of DNA read? So the genetic code was solved, but the regulatory code wasn't. And I thought this was just a really. I mean I'm really interested in life as a mechanism.

A: Uh-huh

B: Uh, but there was something not just purely mechanical. I thought this would be dynamic. That could come and go and change. So that's my broad interest. My specific interest in that problem actually entirely came out of my PhD.

A: Ok

B: I joined a lab which studied that problem in broad strokes

A: Uh-huh

B: But the specific instantiation of that problem was of the type that I just described. In other words, I came in with a broad interest in animals. It turns out that the zoo only has elements.

A: Haha

B: I said, fine, an elephant is an animal, let's study the elephant!

A: (laughs)

B: Uh, the first one is a, is a completely different answer. Urgency. I was at a company that aimed to cure genetic disease, and gene editing was going to be the cure. So I decided to work on that problem because it was gating to the solution to the much bigger problem of sort of --- …

A: Okay. Um. Let's see. Ah, so a question that, not directly about things related to what you've talked about, but that keeps coming up with us is the use of models. So in both of your projects you described, how or when or where or did you use models?

B: Ah

A: (laughs)

B: So, defining models, in broad strokes. Are ab-inicio visualizations, or predictions. Um, of how things work before you start to investigate them.

A: Uh-huh

B: Is that an ok definition?

A: Ah, yeah.

B: So I think the second one is going to be easier to answer.

A: Ok

B: It was very heavily model based. The model was a pretty generic protein, generically interacting with a simple sequence on DNA.

A: Uh-huh

B: This model is the dogma in the field and has been the model in the field since the late 1960s. And in fact, the bl.. the glaring disparity between what I saw early and the model is what drove the entire project.

A: Uh-huh

B: So a misalignment between the model and reality is what drove the entire thing.

A: Ok

B: So in the first project, believe it or not, it was the exact other way. Because as we hit a road block, as we started to investigate the literature, we saw a model, which was partly theoretical, about how this process of DNA repair works.

A: Uh-huh

B: And part of it was demonstrated and part of it was not.

A: Ah

B: But it was sort of in principle, maybe this could work like this. And we said, well, if this is true, if this model is true, then if we change this one variable in our experiment, the following things should happen. And that's what we did. So in my basic science project, complete disagreement with the model drove the whole thing.

A: Ah-huh

B: But bottom line is. I mean, I don't really know. Well, huh. … I cannot think of a single scientific effort of any kind, basic science or tool building that did not have a model as a positive or a negative phenomenon. I just. Yeah. So I don't know of sort of completely unbiased inquiry of any sort

A: Yeah. Okay. Um. … Do you need to go? I said we could try to make it 45 minutes. Do you need to?

B: Has this been useful?

A: This has been great, yes.

one more question asked over e-mail:

A: Thinking about trainees that you've had, what are particular difficulties you've noticed they have when solving problems?

B: 1 - not being able to structure an experiment where there are adequate negative and positive control. 2 - not being critical enough about their data - eg "how do we know this dataset shows X". 3 - being stuck when "something does not work"

Ecology faculty

A: As you know, we're interviewing you, as part of a project to identify how experts think and solve problems during their work and our goal is to identify what students ought to be learning in order to improve education. And so today what I'd like you to do is. Is think about how you solve problems, by having you recall a specific problem or project in your work that you've solved. Or completed. And walk me through the detailed steps, and particularly focus on the decisions you made while solving the problem, and kind of every step along the way that you went through.

E: Whooo (both laugh) Help me a little bit with what scale problem, you'd like me to talk about like is at the scale of how to analyze a particular data set or more like a big. How do you study this problem sort of scale thing?

A: Um, so probably at the scale of a paper so what what might go into a paper. And if we can get into that a little bit about how you would analyze the data set, that would be great because that's also useful information, but…

E: Okay, do you want to be a project that's finished or can it be something that I'm actually writing a manuscript for now?

A: You can do something you're writing the manuscript for now. That'd be fine.

E: Okay. I mean, that's the freshest in my mind. So I think

A: Yeah

E: It's a good one to think through. Okay, so you're probably gonna have to prompt me to give you all of the pieces that you just described.

A: Yeah.

E: So what do you want me to start with?

A: Yeah, so start with, what did you do first? How did you, how did you decide that this was a problem you wanted to tackle. And then what did you do to tackle it?

E: Okay great. Yeah, so, um, I think I got interested when I heard a seminar, about a year and a half ago, about in this question of whether Um. Sort of anthropogenic stressors are making the costs and benefits of migration for animals just, or just changing them, and in ways that are consistently in the direction of not migrating. I got interested in that because someone gave a seminar about it with respect to fishes specifically. And was talking about migration barriers like dams. And fishing. And then sort of benefits to staying put now as the climate, for instance, maybe is warmer where animals previously used to only breed and not over-winter. I thought huh. She was just talking about it with respect to one species, but I got interested in whether that was a general pattern across taxonomic groups and at different scales of migration and decided that it was a question we're trying to answer. So, are environmental changes and sort of making migration go away because it's just not as good a strategy and the context of all the new risks of moving and open the benefits of staying put

A: Interesting

E: So to bite off a problem that big. I mean I guess in ecology. I think about sort of three ways that you can tackle a question like that. One is to do primary research like to go ahead and try to actually, need to look at, movement or populations out in the world and see what's going on. And since that question was really about is this happening in general, that wasn't the right approach. And then the other two are sort of to either meta-analyze the results of existing work that's been done individual cases.

A: Mm

E: And see what, what the pattern is across all of them or to do something in the middle, which would be to try to capitalize on existing databases like the Christmas bird count database for birds in North America. To, you know, do more of a big data like. It's an analysis of raw data, but not data that I collected. Data that people have collected over decades and maybe even centuries. Um. That we could maybe dig into the question with.

A: Mmm

E: That seemed like a really big lift to do the raw data thing. And so I thought, Well, you know the the. This is typical, the first thing you do is you kind of go see what other people have done the topic.

A: Uh-huh

E: So, I went and read papers about. About the evolution of migration and about partial migration, which is a phenomenon and which animals can… A population can have individuals that remain resident year round and individuals that migrate and sort of the fractions of who stays and who goes can vary as a function of changing conditions and. And then I sort of settled on, for first bite at this, not trying to look at everything that migrates, which is again giant gigantic. But to focus on the particular case of partial migrants. Why, because those are cases in which you would expect migration to be able to be very responsive to changing conditions. Um, you have both either sets of alleles or both behaviors president in a population and so you don't have to have an introduction of a new behavior. They're already both there. It's just a question of like whether one's kind of becoming more dominant. Um… And so, that seemed like a size piece to bite off initially.

A: Mhhm

E: So, I mean, I know this is too much detail?

A: No, this is Perfect. This is absolutely perfect.

E: Okay. Um, so that winnowing process. Like, what's a chunk of this as a good representation of the bigger problem when I'm going to bite off. But that's also manageable. Because I think in ecology, there's a lot of fairly case wise thinking. like there's a there's a sense that to extract general principles is, at least from my perspective, it's more of a deductive process. Like we're trying to figure out from the body of evidence out there, what's going on. Because, you know. Every case is different. So, so I started to to sort of try out different search strategies to just identify literature that existed about, um. First, I was just looking for partial migrants and I realized that what I really needed to find were cases in which there was a time series. So a trend.

A: Mmm

E: And those trends had to give me a way to figure out the proportion of a population that migrated and the population that didn't. So those two pieces of information needed to be in there in some way. After looking at many more papers I realized, huh, okay, what are all the other reasons you might see a shift in that fraction that migrates

A: Ahhh

E: And then huh, well of all of these populations are declining. A smaller population by itself, might sort of push you in one direction or the other and so I also need a data on the overall population trend for each case. And. It was very quickly apparent that there were not a lot of data for taxa besides birds and Ungulates. Basically

A: Interesting.

E: And so, and I went, Well, you know, what do I do? I mean, right now I'm actually still kind of wrestling with like, am I writing this paper just about birds where the vast majority of cases were, or am I also going to try to incorporate all these other miscellaneous bits and pieces? One case involving bats and a handful involving elk and deer and sheep, and, you know, one marine mammal case and. And so like yesterday, I decided, you know, I really better try to include all of them, because even if some bit's, a bit piecemeal, there's something to be said for how much information is or isn't out there and whether there's any differences among groups in what's happening or why. So, So then I. So now I had kind of a framework and, you know, had. Had a theoretical framework sort of developing specifically around. Well, you know, what are the mechanisms that drive the evolution of migration or the changes in migration, migratory behavior, that are around interactions between genetic - genetically split environmental thresholds and environmental conditions, maybe. How might the cost benefit landscape be changing? Um, if you're a long distance migratory bird versus if you're an elevationally migrating elk. So sort of trying to formalize my thinking about what my hypotheses should be, and then also formalize my search strategy. So how do I make sure I get all of the papers I can, and I decided I've gotta include all languages and I'm going to, you know, include unpublished literature, but I'm not going to try to analyze raw data. And so I'm not going to do that.

A: Uh-huh

E: Too big. Too big to get a first answer here. And, um, and what data do I need to be extracting from these papers? So I'm using, I was using tools. I found tools to use to sort of reverse engineer what the regression slopes, where the trend lines based on tabular data or data that was graphical but not accompanied by the right kind of analysis that I needed to look for changes and trends. And so figuring out how to extract the data, and figuring out what units everything you need to be in to be comparable. And then at the same time I'm sort of in the background going okay, you know, how am I going to analyze these data? I've done meta analysis before. It's a different statistical challenge than analyzing primary data because you have. You have an additional sources of error, basically. Like you have, you know, you have between study differences that you can kind of just call. Yeah, you can you can (laughs). You have to account for variance among studies in addition to variance among groups in variance within studies and so on.

A: wow

E: But luckily there's this book. It's like sitting here next to me because I'm looking at it a lot lately. Handbook of meta analysis. So, thank God. There's a handbook

A: Nice

E: Um, yeah, the handbook's useful for some things and not for others. Um. You know, how do I fill in missing data? What if there are no variance data or sample size, or do you actually need those to estimate effect sizes. So anyway, bunch of sort of statistical thinking and then figuring out what statistical package in R does approximately what I need it to do. And then. So I extract. So, you know, I did my search strategy. I got like 1800 papers that I needed to search. Whee

A: (laughs)

E: Um, and in and basically my rule was, you know, I was tossing and paper because I didn't have anything useful in it. And I just tossed it, put it in another folder over there. But if I was in tossing the paper. And it had something useful in it. Then I needed to search all of the references of that paper and forward search everyone who'd ever cited that paper so it all took a while,

A: Yeah

E: And and this was not a project that decided to bring in a student or anything to work on, because I had, you know, like I think if it gets bigger and we are going to analyze raw data or do a targeted case that's the right taxonomic case to nail down some like missing piece of the puzzle. Then I'll bring a student on but I'm just doing this myself understand what's going on.

A: ok

E: So in the end, I had about 50 or 60 cases of birds. Yeah. And like I said, sort of just a handful of other ones. So I analyze the bird data first on its own, rather than trying to smash all the taxonomic groups together because they seem really apples and oranges and just did two kinds of analysis, one was just sort of across all of these cases, around the world. Is there a significant direction of change in the fraction of these populations migrating? And the answer is yeah they're declining. And then the second kind of analysis was like well, why? What and, you know, so that's this process of trying to unpack, like, Well, what are all of the reasons that might explain differences among the cases and how much changes have occurred and what direction. And so there's a latitude piece that has to do with how much temperature change there's been over time and how severe winters might be for the wintering populations. And then there are pieces like taxonomy and life history. And, uh The length of the trend that was studied. Maybe you're studying a longer term you see more change

A: Ah

E: Per year then then if you're studying a shorter trend or if it's more recent. So when did the trend end, since change's been happening faster and, you know, trying to gather information from the study about what the authors were attributing the changes to. And put all that together. And, you know, feel like the preliminary answers are, they're partial. Right like, for birds that winter at high latitudes, there's a consistent decline in migrating fraction. It's across all taxa, but most of the ones have been studied are in Europe.

A: Hmm

E: So, you know, and almost every single study is pointing to climate change is pointing to. Well, the ice to be frozen and as melted. So the ducks can stay. or the. You know, there's more food in the winter and

still easier for things to just stay. So that that was kind of the overwhelming picture but I guess I feel like at this point. What I'm seeing is the picture for a different group, for the terrestrial mammals that walk, the picture's really different and. So they're all totally declining in migration too, but the reasons why are really different. Um they seem to be really different. from the cases I'm seeing it's all to do with land use change and hunting pressure and with fences and things like that. So, that reflects differences in their biology, I mean they're not just able to the fly over that stuff.

A: Right

E: So, um, I guess you know. So far that what I see is that there's a partial answer because there are only certain groups that have been studied in certain geographies, but the partial answer is, like, based on what people have looked at yet totally there is a decline across groups occurring in, in migration, and this is sort of separate from the question of whether there's a decline in migratory species occurring because they're dying more. This is about, you know, are they either deciding behaviorally or undergoing selection in favor of giving up migration? And um. So, I mean, I think, you know, for me, as an ecologist, great. I'm at a point now where I write a manuscript about this. But then it's raised all these questions and I think, you know, the next question is sort of like okay well what don't we know? What did I not get the answers do here and, And so I don't feel like I necessarily know the right, the right next step is yet but

A: Okay.

E: I guess I'm talking through this part of it because I think it feels like usually this is what it's looked like for me. It that there's like this iterative process. Sometimes it starts with it and meta-analysis and when you identify holes and you go figure out what to do next. And sometimes, it starts with the case. Like we're trying to understand a particular species biology in relation to environmental change and. You know, and then after you, after you figure it out for that species and you want to go, what, what does that generalize to? what do we learn from that that we can apply to others? so I guess there's a there's a deductive and inductive part to my work. But both of them end up you know usually pointing to the need for something on the opposite side.

A: That makes sense…. So you were talking about that you figured out reasons why the birds were decreasing and migration, the mammals, we're decreasing. Can you talk a little bit more about how you identified those reasons?

E: Yeah. Um, I think, you know, for this kind of this kind of study is a funny example to be talking about because it's not primary research so

A: Right

E: If it were a primary research thing. You know, I'd probably have to like, do some kind of experiment or, you know, there would be some different looking process for this one. You know I'm I'm finding out what other people have done. Okay, so I'm reading a paper, it has data in it. I include the data in a meta analysis, sort of, statistically, but then I'm trying to read the paper is fairly carefully for like what motivated a study? Why do they think it's happening. Did they do some kind of analysis to relate and northern Atlantic Oscillation index to the fraction migrating in each year, like so. So when I'm attributing causes in this particular kind of project. It's a real range. It ranges from studies in which there was a pretty rigorous statistical analysis of the relationship on an annual basis between like a climate variable and the biological response. To cases where, you know, kind of at the end of this discussion after just

kind of speculating a bit, yeah. Seems like it's, you know, corresponding to a trend of increasing stubble left in the fields by farmers, because it's not covered up by snow. The birds can access it. And it's just speculative. and You know, I have not weighted those sort of strength of inference.

A: Ok

E: I could. There are ways to do that. Like I could sort of assign higher weights to studies that actually establish some sort of at least. I mean, none of them are experimental, right, they're all observational studies which is. That's the hardest, you know, the hardest situation, you have to kind of really make the subjective assessments about whether they know. That right, whether they might be missing something that didn't even talk about in the paper. Yeah, so, so I'm taking the author's word for it on some level, but you know, I'm also making a subjective assessment. I mean, you know, if they're really just speculating all over the place. I'm not gonna. I'm not going to put anything in.

A: Okay

E: Yeah. And sometimes they have nothing to say. And then that's another question for me. So do I circle back to those and try to understand, whether in those particular cases there is a relationship between climate and land cover changing. I mean it can become a bit of a fishing expedition. And that's not my favorite way to do hypothesis testing. I would rather sort of. Say, Okay. Well, I think it's specifically this on a look at specifically this, and it either is or it isn't. Not, you know, it could be this, you know, it could be 67 different things. So I'm just going to run this giant data mining effort. I feel like ecology is gone more the latter direction.

A: Ah

E: I'm Not thrilled with that. You're always gonna find something if you look enough

A: Right. … So. Okay, I guess it would probably have to be a different project, but can you talk a little bit about something where you did do hypothesis testing?

E: Yeah, let me talk about a different project. And let's see. I want to think of a really nice clean controlled one. Okay so different study. Um, trying to understand whether nitrogen deposition and nitrogen pollution was sort of imperiling native endemic plants in California serpentine grasslands, by promoting the competitive ability of invasive plants. So we had a field component to that which was. Um. We had some different field components to that. But I guess I guess to drill down to this one. I wasn't. Yeah, we were looking at, like, hundred year trends and atmospheric deposition in tree rings and we were looking at gradients of deposition and from right next to Highway [X] to far away and doing a lot of observational work like that. But to really drill down and look at the to test the hypothesis that you know, by putting those particular forms of nitrogen into the soil of these relatively low rates we are sort of shifting the competitive balance. We actually just did some greenhouse experiments.

A: Hmm

So we just. Had, you know, replicated little growth chambers with. With either just the soil inputs of nitrogen or also like the NOx emissions actually like pretending the little growth chambers and had, you know, had two native species and one exotic species and grew them separately and, and then pairwise, and looked at how different so. Control soil nutrients enhanced atmospheric nutrients enhanced, both enhanced, have shifted competitive outcomes as measured by germination and growth rates. And.

Yeah, so that has helped us nail down and show much more definitively than anything we could do in the field that. That additive effect of the soil and the atmospheric pollutants and it's. It's right. It's, it's not just one. the additive effect they have on growth in the invader end up having sort of a multiplicative effect on how poorly the native species fares and, you know, so help us understand cause and effect, but also a little bit more about the interacting. The interacting nature of the two kinds of pollution and how they are. How they end up being multiplicative in their effects. Via the changing competitive outcomes. Is that the kind of thing you're talking about?

A: Yeah, yeah, no. that was great. Yeah.

E: great

A: Um. Looking through my

E: That was a boring example, but

A: No, That's a good, a good illustration of the process. So, um, So one question, or maybe related that one is. Were you considering like multiple different possible hypotheses, or were you really just, we think it's this?

E: Um, I guess we were considering a couple of different hypotheses. I mean. considering hypotheses. So Sometimes you considering hypotheses that include some that you know not to be. Are you pretty sure aren't right. Right. I can't, I can't say no. But, you know, so. Did we expect like the Nitrogen pollution to enhance growth independently of like both species. Well, Yeah. But of the invasive more. Well, yeah, but then you know when competition. I think that you know that the one hypothesis was that the atmospheric deposition just was kind of beside the point. And didn't matter. And then it was all going to be about accumulated soil.

A: Hmm

E: Nitrogen. Is, you know, that it had already undergone some transformation. And then the other possibility was that the atmospheric piece, as atmospheric inputs before it'd undergone soil transformations was also going to be important. So we didn't actually know the answer to that part. Yeah, and I think we were also interested in whether you know you could predict the competitive outcomes from the individual responses of the two species. Like the native and the exotic nature, the two species cases and. The answer was kind of no. Because, you know, they both grow better alone, but

A: Hmm

E: When you put them in a situation where they're competing, even though one grows, the native one grows better when it's by itself, it actually grows less well when it's experiencing the fertilization but also in competition with this invader hat's much more able to capitalize on those nutrients and then gobbles up other resources that are not available to the native

A: Interesting. … Okay. Um, so in in either of these projects. What do you think were critical decisions that you made?

E: (laughs) Critical decisions… I mean, I think the most critical decision in the in the meta-analysis that I was talking about this sort of how to confine the problem, at least initially.

A: hmm

E: In a way that made it feasible to bite off, without making it a skewed or an unrepresentative picture of the thing we're looking at. So I guess I mean, to me that's the most important decision because I keep having to circle back and go, Okay, well, but this is a trend for partial migrants and so. Does that tell me about what's happening in obligate migratory populations? I don't. I Have to be very careful about that and really understanding that depends on what the biology of of migration is and it probably varies somewhat by taxonomic group and by case. And so like I think the representativeness of the case that you choose to bite off is like that's the biggest decision.

A: Ahh

E: Is this a case of the bigger thing that I'm wanting to understand and. All the other decisions are like a more technical little decisions. Yeah, even, even at the level of, you know, do I analyze a bunch of raw data from these giant databases or do I just start out with a published literature. That is a small decision compared to you know the case. So that's one. … You know, and these observational studies in ecology, you have, I think I feel you have to make some really thoughtful considered decisions about what to include as potential explanatory variables.

A: Hmm

E: Because, You know, maybe it's just the way I was trained and I've been doing science for a longer time. So I'm not as much of a big data cruncher but. You know my feeling is that you really have to be thoughtful about not excluding things that might be important. On the one hand, but on the other hand, you can't do. I do not feel that you can do a giant fishing expedition. I mean. you know when you're looking at the world, you can't put in everything that might be related in some way. There has to be some sort of, you have to do some discriminating around like what what biologically makes sense to include. And sometimes also what makes sense to include from the standpoint of, like,. Um, what am I trying to say here, I mean, I want to be careful with this, the things you exclude because they're irrelevant. There things you exclude because they're not what you're studying in this particular study

A: Uh-huh

E: Maybe you have to pull them in later if you find out that the things you were studying are not telling you what you need to understand, but you don't want to start there. Yeah. And then, I guess, I don't know is there this. No. I'm disagreeing with myself before I think. Okay, but that's another that's another important set of decisions, I think. You know, in an experimental sort of situation. I mean, that's, it's a much more clear decision thing like you can have one or two or three or maybe even four factors that you cross but like that's it. Four is kinda it.

A: (laughs)

E: My dissertation project actually was like for cross factors. It was like, you know, pushing the edge of ridiculous in terms of design. Cause it had 16 treatments, we had like high and low warming, high and low carbon dioxide, high and low nitrogen deposition, high and low precipitation. All crossed. And like part of my dissertation work was like figuring out what to do that statistically

A: Right.

E: So I think when you're doing an experiment experiments. You know, it's much more clear, you have to kind of make those decisions and focus on one or two or three things. But in so much of ecology, and I think the ecology that's the most relevant and understanding how the world works. You know, you are using these big observational data sets and. Boy, there's no limit on how much stuff you could try to put into them, but I like parsimony

A: Yeah

E: Like you know, you really got to… Still focus on not too many things at once. So that's really important decision. Space. And then interpreting what you found. Because it's seldom very neat and tidy in these observational sort of contexts, like I think interpreting the outcomes of an experiment with four treatments. That's more straightforward. Doing it when you have. … You know you have a mess.

A: Yeah

E: You have you have. Yes. Yeah. You're 95% confidence intervals around a value that don't overlap with zero. So that's pretty reasonable confidence that like there is an overall pattern, but there's so much noise around it and making sense out of that noise and sort of. Especially, you know, where you're looking at across many different species understanding at least intuitively how much to make out of that noise. As explained by other specific variables like okay well there's all this noise but you know maybe latitude helps us explain some of that and taxonomy maybe helps us explain some of it, and stuff like that. And then at what point to say "These are all different species whole bunch of other differences among them. Like, what kinds of habitats, they live in?" I mean, there you know. Sort of time to first reproduction is and it is a bazillion things that we are not going to be able to attribute specifically to anything and just going to say this is the variation you know among different species or different taxa. Um. It's because they're different.

(both laugh)

E: And yeah because I think I think in ecology. There's, there's, there's often a desire to overreach. I remember, especially when I was a graduate student and postdoc, it is sort of learning that art of how to interpret what we found, and feeling like there's a lot of overreach sometimes and desire to generalize about other cases from your one case.

A: Uh-huh

E:: As opposed to just let it be a proof of concept, but it's possible that this explain that. But not that means that it's often or, you know, always the explanation. Yeah.

A: So how. How do you decide when you the evidence, you've collected is enough to to publish or to or to move on to the next step in your project?

E: Yeah. I mean, I think, you know, in a case like this. I kind of feel like what we get is. Um. You know, meta analysis, you have to exhaustively search was out there. And then once you've actually done that like you had a plan and you followed it and you exhaustively searched what was out there and. Every new, you know, whole you go down, this leads back to one of the places you've already been. Then you're done. And you can write it up. Heh, my tendency is to feel like you know. When is it time to publish? I think there's always this tension between, you know, publishing little incremental stuff that's kind of like, Oh, come on. You could have waited and made more out of that first and then published

something that was a little bit bigger, on the one hand. And getting information out there on the other hand. So that other people have it to work with. And to sort of drive their thinking about the related things that they're doing so. So what does that mean?

(both laugh)

E: Um, I do think it's important to publish things when they're done. And so, like, and so in the case of this meta-analysis, you know it's it's basically it's done. I can go down a couple more rabbit holes to see if they'd lead me anywhere new but I pretty much like just doing the, like, all right, I've been here before. Um. Done enough to publish a paper. Not done enough to say, okay, now we've answered this question - on to the next one.

A: Ok

E: But in field experiments. I mean, I think that's sort of worth, worth saying something more about too. Because I think in ecology, you know, there's so much contingency around like. Well, did you do that study in a wet year or dry year or a cold year or hot year, or a year there's a lot of smoke in the air? You know, it was recessions, so there wasn't much nitrogen pollution. I mean, so. For field experiments my tendency is to feel like, you know, really, you owe the literature, three years because. And and I've done most of my fieldwork in California where things are especially variable from year to year.

A: Uh huh.

E: You really want to be able to say not. Okay, so here's a pattern we saw one year, but we saw this across three years and almost inevitably the three years are really different, you know, it's usually a pretty wetland. And a kinda dry one and maybe an average one or something like that. And at that point, I feel like. Either there's a story about how you see a consistent response across those various conditions or there's a story about how the response totally depends on the conditions, and it takes three years to understand that. So I don't like seeing field experiments that only last year, very much. Yeah.

A: Okay. Um, so something that in talking with [Name] that came up was that like Sometimes, you start with a question. And sometimes, you start with an observation. And so I wanted to get your perspective on like. You know, does it matter, when's what you know what do you tend to start with?

E: That's super interesting because. Sometimes it starts with a question. And sometimes, it starts with an observation. Yeah. I mean, ultimately, I think they all sort of harken back to observation in some way or another, but for a specific project. Yeah, I mean, I think that's right. Like, I've done both kinds of projects I've done projects where. The question is, well, you know how do climate and atmospheric changes interact and do the act like additively or is there some crazy synergy. And what's the right system to test that in? and then you go tested in that system and you kind of have totally started with a question. And then I have projects where I mean this giant project about these birds Rosie finches where. For me personally, you know, they all started landing on my roof one day, one winter.

A: (laughs)

E: And literally, the questions like, Well, where do they come from. So you go and read what you can find. And then you realize like, oh, don't actually knows. Where they come from. What?

(cut out, some lauging)

E: I think ecology, though, you know, there's quite a lot. You can see like, it's not a. It's not a field that focuses on scales that are invisible. Without a microscope or a telescope or, you know, a collider or something. So I think, you know, yeah I Primary. I mainly teach about observation is sort of the impetus for for question generation. So. There's observation, question. Go find out what people have already done. half the time they've already answered the question for you. Great. Once in a while, they have it. And then you've got and we've got a research project. So I'm. Now, I can't remember exactly what you asked me, like what observation versus question generated projects.

A: Yeah, I just wanted to get your perspective. Yeah how frequent. They were so yeah

E: Yeah, and I think there's another you know there's another piece to the way that I've seen work unfolding ecology, which also has to do with how observable ecological phenomena tend to be and that is that. Um, I think it's really good to get a project started in a location that that is understudied or that has conservation value. Often, because what will happen is you have an initial thing you can do there. And then the process of being there, and learning about the place, always ends up generating all kinds of projects that often have more immediate value to the place that you're working. So what I keep seeing are these cycles of like you initially swoop into a place with an idea that sort of preconceived that maybe has to do with what it's a good system to look at. And then you end up generating projects that are much more refined by observation, not only of the system, you know, and how it works, but also of need.

A: Hmm.

E: So I think that that's a. Kind of in a way that that has unfolded for me as a field ecologist

A: Great. Um, I have, I think, just two more questions. One is, Like so it'll with a lot of people. We've talked about their use of models. And so I wanted it to hear about, you know. To what extent were you using models in the two projects you've described and, or in general, how do you use models?

E: Okay. And do you have any anything in mind, particularly when you say models because there's so many kinds of models.

A: (laughs)

E: There are conceptual models and theoretical models and computational model. Yeah.

A: Yeah, so, so I guess I'm thinking a model in the sense of the the, Your understanding of the key factors and the relationships between those. And that can be manifested in a computational model or in a theoretical model. So, but, but that your understanding of the factors and the relationships between those

E: Yeah. I mean, at a conceptual level, you know, I'm one of those like box and bubble people. So that's the conceptual models sort of drive all my thinking was making you know. And getting my students to make pictures of, you know, sort of trying to understand the relationships among variables by visualizing them. And, you know, putting thicknesses and arrows and putting. So that that's not a mathematical model, but it is a conceptual model. And that's super, super foundational to how I think about ecology because, you know, they're kind of ecological systems you can you can bite off a piece and focus in on it,

but I don't think you can do that, you know, until you've really. Explored what all the other parts of the system are around it and decided that it's reasonable to isolate this piece to focus on. So, I mean, I guess I use conceptual models to figure out, like what's reasonable to make external to my study and like what I need to control for and what I need to. Yeah, incorporate as a variable. So in terms of other kinds of models. I have not done much theoretical modeling like developing you know equations to describe what what's going on in my system. And. You know, I use a lot of statistical modeling. To. I mean that's that also is a different kind of modeling. I don't really think of that as like the kind of modeling people are usually referring to.

A: Uh-huh

E: So I use a lot of statistical models. (don't?) use lot of sort of algebraic or mathematical models and then computational models like simulations. I personally have not used very much but I often have had collaborators who do use them. So to drive. Um. I'll give you an example. So right now the the project on those birds that started on my roof. We are. We want to understand that they're. They're these really high elevation breeders. I'm looking out the window at the mountaintops. They breed. You know, sort of 12,000 feet up to the tops of what's available in the southeastern US in the Sierra Nevada. Um. So … worked. We're interested in what's going to happen under climate change to them, are they going to move north, are they going to like disappear off the tops of the mountains are they just going to be generalists because they kind of are, and start doing something different? And what is it that is tying them to those mountaintops and snow and so on. So, there is a part of this that is doing some pretty intensive model development to incorporate sort of the ecological constraints we're learning about, and then genetic variation across the distributions of the species into a sort of joint ecological and evolutionary model driven, you know, with global climate model inputs. To look at what their distributions might be in the future, and what sort of allele frequency landscapes around key traits maybe in the future. But that's not me.

A: Ok

E: That's like the Bayesian climate modeler guy who that's what he does. And I do feel like I've uh, I've been encouraged throughout my career to, to not try to do everything myself and that's one of the things I've gone like 'okay, I'm not a modeler." So I think they're really important sometimes to sort of, um. Understanding the implications like really well of what we found. And I've done that kind of thing in the past with other species too, like where we take a bunch of information we've gathered through this sort of field based understanding of the ecology of a particular species or community. And then we've modeled it up under climate change or with different assumptions about fire in the future. To try to see what that means for down the line.

A: Mm

E: So as a as a way of projecting or testing hypotheses about which assumptions really influence your expectations for a species and the future. Yeah.

A: All right, great. And so then my last question for you is thinking about students or trainees that you've had. What. Are there a particular difficulties in problem solving that you've noticed in them or differences in the way that you approach problems compared to them?

E: Um, poof. I mean I, one of the things I feel like I've learned is that every single one of my students has like a different landscape of strengths and weaknesses and things that are easy for them and things that are hard for them so

A: Sure

E: I think it's super individual. And I'm. And I'm thinking more about graduate students there. You know, I think that for. For. Honestly for graduate students. Yeah, really, all different, but to some extent, you know what I

A: Heh

E: what I do feel like I consistently am trying to work with them on, it's like working backwards from the kind of story that they want to tell, or stories that they want to tell, with their dissertation backwards through. What does that mean, like, for the end. and the kinds of skills they want to have at the end of the process. What does that mean for what kind of project you want to do for all the chapters. Do you want to have. Do you want a meta analysis chapter do want a modeling chapter do want an experimental component? How important is it to you to have like You know, three chapters that are one story as opposed to having three chapters that illustrate your ability to take this one tool and applied to three different kinds of problems. And so that kind of big picture planning. I feel like I've had, I've had to do that with everybody.

A: Uh-huh

E: Um, But with respect to like sort of how people tackle. Problem solving… I think. That's a really hard question. But there's a piece of it. That's like. The thing that I was talking about, about sort of identifying the part that you can isolate that you can do that is the right size for a dissertation, especially. But that is not a distortion of the bigger question that you're wanting it to speak to. That piece. That can often be hard for students. Like at any scale, even at an undergraduate scale. Now, it's not just what the right size pieces because that's always a challenge too. Right, like everyone's ideas like way too big or too small or descriptive as opposed to hypothesis testing. I think in ecology, it's you know, it's easy. Sometimes your students just want to like describe what does this bat eat? That's what I want to study. But Hypothesis! Get me from general biological difference of principles to like what you think is going to be the outcome and how studying is going to tell you something new about the biological principles. That sort of, um. Building theory at the same time as you're learning about the specific cases that you're studying. And then picking that representative case to focus on and then often it's also like designing the study in such a way that it really does do justice to the theoretical question and the hypothesis, as well as the good natural history that's going to actually give you the right answer. I mean, everybody's different. But for me personally, I see ecology focusing more these days on, On data mining and data manipulation and it's concerning to me because what I see is that. Where people really become good thinkers about what's going on in their system and good interpreters of what's happening and, and good at making those decisions about what might be important factors to look more deeply at and what they can just ignore, is by spending time in the system.

A: hmm

E: So these birds work within the mountains, man they are bear to work with because you can always go up to like just where you're passing out from how high it is up and it's freezing and it's like a 14 mile hike to get there, but, um, there's no substitute for getting up there and watching them. And if somebody

just gave you like all the data you could possibly want about snowpack, and temperature, and insects, and plants, and phonology and every conceivable thing. You could never figure out what matters to the birds. You actually if you want to understand and define their niche envelope, you have to go look

A: Mm

E: So sort of helping people sort of strengthen that bridge between observation and interpretation of what's going on in the system and what matters and what to focus on and what to ignore, and then how to design a study around that. Or how to bite off these pieces. And then helping students dig into mechanism. You know, like, what do the birds eat? Meh.

A: Yeah

E: Yes, we need to know that, how do we. You know, how do we how do. What really is the question? Like. How dependent are they on snow maybe is a question that's more kind of like feed into understanding how snowpack decline is gonna affect them. So how do we answer that and like what tools do we bring to bear on that? and, you know, it starts with, well let's just watch where they eat. But then trying to help them pull in like we could use stable isotopes, and we could use like maybe we could use the genetics on fecal samples like. Yeah, Trying to bring in different kinds of tools to to answer questions. In ways that are more mechanistic. Maybe. Okay, I'm just rambling.

A: No, It's Been really great. So as you were going through your projects. I was just like, like check check check off of our list of. What we've identified as decisions and decisions that people make so so ecology doesn't seem different. I mean, they're all Different sides and different different questions. But the overall, the way you approach problems is like, yes. Okay.

E: That's really cool.

A: Yeah, so, so thank you very much. This has been really helpful.

Immunology faculty

(recording started late)

A: … learning new technologies

I: yeah, because I think that is something that people come into a lab and you often times want to use a new technology that hasn't been used in the lab before

A: Yeah

I: And so that is always a challenge. How does the student pick up the skill set to do the, to learn the new technology

A: Uh-huh

I: So what are various methods you can use? Certainly you can ask them to read about it. You can ask them to identify someone else who is using that technology and see if it's possible for them to, um, … shadow them. Sometimes it's even possible to spend money to send them to a different university. And I've done that before. Have the person go there, spend a few days, and come back. Another thing is if there's a video about the method. And then when they come back to the lab, the question is are they going to be able to really do it?

A: Right

I: And sometimes there's little things. Maybe they didn't have the right kind of plate, or maybe there was some detail that they missed. So you need to have some expected, um, expectation that if they do this they should get this result.

A: Uh-huh

I: So something that's been done before that they could duplicate and see if they are actually able to duplicate a result from a published work or something like that. And have the right controls to see. So if they can't duplicate work that's done with the same technique, then there's something wrong with what they're doing and they need to try and troubleshoot. So then you ask them what it could be. I think it's important, as much as possible, to um, elicit things from the student

A: Mhmm

I: And not to tell them anything initially because you want them to take responsibility for their project. And they're the ones who are actually doing the work hands-on. I think one thing I've learned over the years as much as possible is rather than assign things to students, as much as possible allow them to make choices and do things that they are really interested in. And also if this is something that they care about, then they're going to do a better job than if they're just doing it because you want them to do it. And so that's another thing I think it's really important as much as possible to have students doing something that they really care about and they're interested in doing and they'll spend more effort on it and do a better job. So then you, um, ask as much as they can, look at the data. Maybe you can help troubleshoot. Maybe you can suggest others that they could talk to. Um, so that's what I was thinking about in terms of…

A: Mhmm

I: Another skill is maybe not a technological thing, but communication. Are they able to communicate with others? And communicate not just for scientifically literate people in their field but also others. … (thing popped up and distracted) … so um, communication. Not just for scientifically literate. So for instance, I had a postdoc who was interviewing at a company

A: Uh-huh

I: And when you go to interview at a company or maybe even at a biology department, people aren't all in your field. They're in a variety of fields. And I thought her talk was much more specialized

A: Mhmm

I: And wasn't appropriate for a broad diverse audience. It was like she was speaking to someone in our immunology research in progress

A: Right

I: You know all the same people in the same field. And then people have different habits. Some people are more effective at communicating than others. So that's another thing. So I think. We have a teaching and learning center. So I like students and postdocs to at least take one course on scientific teaching.

A: Uh-huh

I: So I think by learning some teaching skills, they'll also learn some of these other skills. And then of course having them do practice talks.

A: Uh-huh

I: I really think it's important for, in lab, to have a person doing practice talks so they can get feedback from others. And give them as much opportunity, but also give them feedback. You can't just have them "practice.' So that is something that I think is also a skillset that is needed is communication abilities. And so that's another thing. Now in terms of assessments. You know, we don't really do much in terms of assessment, quite frankly.

A: Yeah.

I: If I think that they learned the technique, then that means that they did it or they didn't.

A: Right

I: Communication. Um, again, I can give them feedback, but that's all I'm doing in terms of the assessment, quite frankly, is that. but I don't think we do anything in a more systematic like if you were teaching a course

A: Right

I: You get some assessments back in terms of the evaluations. So I think that's um, something we don't do or think about.

A: Mhmm

I: And maybe we should be doing more of thinking about assessing how effective we are at teaching various skillsets to the students

A: Yeah

I: So. I guess, I guess that's about it that I was thinking about.

A: Okay. Um, so thinking about the learning new technology, can you think of an example where there was a project where you had somebody who needed to learn a technology, and actually walk me through what that project was and what they needed to learn, and how they went about learning it and what you did in that process?

I: Yeah, so. Let's say, uh, we were measuring. We were making some affinity measurement of um, two proteins. And they talked to a person that was no longer in the lab that had done it before, gave them some. They talked to some other people in the lab. And then they did it and it wasn't working that well. And um, it turns out that the person who initially taught them didn't tell them that we needed to use a certain type of plate

A: Oh, hah.

I: So the plate they were using was not the appropriate plate for doing the assay. And um, so. The data wasn't very good. They were just here for the summer.

A: Ok

I: Well, no, they were here for a little bit longer, but something like that. so it made me realize how important. I always know that the details are important, but I think I probably should have spoken more to the student at each different step and asked them what are you using for this? What about this? Give me a very detailed protocol for what you are doing, so we can then show it to the person who did it before and see if they can help troubleshoot also.

A: Uh-huh

I: So that's. that's an example of, you know a project.

A: Okay, yeah. Um, so. Let's see. Thinking about, um, … like, … I guess maybe a little bit a bigger picture project? Like can you start from what is the research question that you had somebody working on, and talk through not just an assay, but starting from the research question and then talk through how you go about, uh… working on a project?

I: Okay, alright. You know what then, if that's what you want, I think it would be better if I outline it before hand and prepare a little bit more for this question

A: Okay, sure. Sure.

I: So maybe we could talk again [another day]? Would that be okay?

A: Oh, yes. [discuss scheduling]

Interview 2

[recording missed general intro/question]

I: so I had a postdoc working on it. She was working with somebody else as well. And we looked at the sequences of the different isoforms and trying to make predictions about what might be binding to the isoform.

A: Uh-huh

I: The other thing they did was try to separate lymphocyte sub-populations and look to see what the expression level was like based on RNA. We also tried to see if we could generate antibodies specific for each isoform, so we could specifically detect not just the message but the protein. That was minimally successful. We sent the material to a company

A: Okay

I: And in one case we got a serum that seemed to pull down one isoform but it didn't work for the others, partly because the specific areas of the isoforms weren't that different. Um, but anyway I don't know all the details, but it didn't work. So we had to rely more on RNA expression levels. Um. And then after we studied expression and we made some predictions on what it might be doing in the cytoplasm, then we tried to test the predictions, and um, so we looked to see um, if it was ubiquinated. We set up assays to study that. we also created cell lines that would be expressing each isoform separately.

A: Okay

I: Um, and then as a functional assay we took the mutants that seemed to have some property that was no longer um, retained. And put them into a human T cell line to see how it would affect the function of this CD8 protein. And that's as far as we got.

A: Okay.

I: We have one more thing we're testing now, in that we made another prediction that it would. That one of the isoforms would interact with a certain protein that's involved in clustering of receptors. So we want to try and study that. so we set up a collaboration with another lab that does TRF microcsopy. So we're creating the cell lines with the receptor mutant or not mutant, and linked to GFP so that we can monitor it's clustering properties in cells, and we're collecting cell lines with that. so that's sort of where we are with the project right now.

A: Okay, so. … going back to the, um, the step right before where you're at right now, so you um, you mentioned that you had a prediction that it would be ubiquitylated. And, so, how did you come up with that prediction, and how did you go about testing that?

I: Um, we looked at the literature, and also some, um, websites that make predictions about potential interactions with certain sequences.

A: Okay

I: And um. So it was both a literature as well as web databases with prediction programs.

A: Okay. And so this was one of the isoforms, and you had

I: Predicted.

A: Yeah. So can you tell me a little bit more about the different isoforms and what was known about them, and heh.

I: Well, people had. People had said that there were different isoforms

A: Okay

I: When they were cloning the gene they found some variants that had different cytoplasmic tail. And so we did a more careful analysis to really analyze what specific sub-populations the isoforms were located. And nobody had studied the functional significance of them. So that was another thing we were doing. They were reported, and we did a much more careful analysis of them. Both through their expression patterns and functional. And also how might they be mechanistically impacting an immune T-cell response because of some of the properties of proteins in the cytoplasm they would interact with. They only differ in their cytoplasmic tail

A: Okay

I: So we presume it's all a matter of signaling.

A: Okay. Um, so … okay, so let's start with the um, RNA sequencing then. So, I imagine it was a postdoc who was doing the, the you know bench work on this.

I: Yes

A: Um, so what. When you're working with the postdoc, what were the decisions that the postdoc was making, and what were decisions you were making?

I: Um, well, I was making the decision of the goal of the project.

A: Uh-huh

I: And I would say the postdoc was determining how best to separate the cells into different sub-populations, and then some of the technologic… techniques that would be used to do the analysis. And you know, we discussed it, and I would agree. So that's what we did.

A: Okay. And, so what … let's see. As you were sorting the cells into different sub populations, like, what did you find from that?

I: Oh, well, she saw differential expression. So the RNA patterns were different depending on the cell population that we were looking at. And the tricky thing was getting probes that were specific for each isoform.

A: Okay

I: Because some of them had very similar sequences, and it was just a very small region. So it was tricky to actually create a probe that was relly specific for each isoform

A: Ah

I: And so she, she did that. Because sometimes it was just a matter of the splice site. So it was looking at the splice overlap. Because some of them were using similar exons, so we couldn't just go look at the exon, we had to go look at the splice junction

A: Okay, wow

I: So that was tricky. But she figured that out. She probably is the one that created the probes that worked. You know, we probably discussed what region would we have to use as a probe, because of the overlap.

A: Uh-huh. … And so, so you sorted. I'm just trying to see if I understand what the project was (laughs). So you sorted out the cells into different sub-populations, you saw different RNA expression in the different cells, and so then, and that there was this technical effort to identify the RNA. Um, and so then you know, what did you do next?

I: Well, then we thought, okay, different cells are expressing them differently. So they must have a functional significance that's relevant to each of those cell types. So then we just tried to understand what would be the functional relevance. For instance, one was predominant in a naïve t cell. One was predominant in a memory cell. So how would they contribute to the properties of those two cell types?

A: Okay

I: So that was our hypothesis. … And then we looked at what are some of the differences in the properties between those two cell types, and asked, could these isoforms contribute to those specific properties?

A: Okay. … And so how did you test that?

I: Um, well, we put them into a human T cell line, and then tried to stimulate the cells and look to see for differences in responses when they had different isoforms. And then, um, as I said for instance, the T cell receptors clustered, but differently in a naïve vs. a memory. So now we're testing the possibility that this isoform that's in the memory contributes to clustering

A: Uh-huh

I: And it has some properties in its cytoplasmic tail that it likely interacts with certain proteins that could contribute to clustering. So based on that we made the hypothesis and we're going to test that now.

A: So that's where you've created the cell lines that you're sending to the other lab to do fancy microscopy

I: Right

A: So the assay that they're going to do is what?

I: They're basically going to put a ligand and look for clustering, to see what. How the T cell receptor is normally clustered on these cells, with or without our two isoforms.

A: Um, okay. So, in this project, what were critical decisions that you think you or the postdoc made?

I: Well, one critical decision was trying to figure out a probe that could distinguish them. That was very critical. Um. Another thing is, um, making predictions, or hypotheses, based on the sequence of the cytoplasmic tail and then what we know about T cells and how they function and differences between functions. We also had one interesting finding in that one of the isoforms that we expressed in a mouse, of the four. Three of them went to the cell surface, and this one didn't. And we couldn't understand why. And we kind of ignored it at first, and we finally figured it out. Um, because, it has a potential for poly-ubiquitination. And poly-ubiquitination leads to degradation of proteins. So we tested the hypothesis, we mutated the lysine that we thought could be poly-ubiquitinated, and now it came to the cell surface

A: Oh, interesting.

I: So it's regulated by poly-ubiquitination. The other isoform is regulated by mono-ubiquitination, and that affects trafficking, not degradation.

A: So, you mentioned the.

I: So we had an unusual finding, and we couldn't understand why. And we later went back and tried to figure out why.

A: Uh-huh. So what, can you tell me a little bit about, like, when did you decide that it was worth going back to, and how that decision worked?

I: Well, at first you're just trying to get some results. So if your other three proteins are being expressed, you say, well, let's just move on with that. Because that's something that we can potentially publish and it's interpretable. And I think it's just in the back of our minds, why is this not expressed?

A: Ok

I: And somehow over time, we thought about it, and one of us came up with the idea that maybe that's why. So we just let it simmer for a while.

A: (laughs)

I: We didn't. Sometimes when you don't know why something is happening, it could take a while to figure out. And you don't want to go on a path that feels like it doesn't go anywhere.

A: Yeah

I: And so you have to feel like you have a good idea about what might be happening. And then you test it. Cause there's no point in working on it if you don't have a good idea for why it's happening.

A: Right

I: And so sometimes that takes time to come up with an idea.

A: and so then once you had that hypothesis, how did you test it?

I: Well, we just, we know poly-ubiquitination occurs on lysines,

A: Oh right, you said.

I: This had a lysine, so we just mutated it and put it back into the cells and asked, is it expressed now? And it was. So we realized this is a mechanism for regulating the expression of this isoform. And that's a way for proteins to be rapidly expressed. Because the message is there, your protein is there, but it's just being ubiquitinated. So if you stop the ubiquitination, your protein is going to be expressed in a very short period of time

A: Uh-huh, right

I: Because you're already making it. So at some level, there's an advantage to the cell to waste the energy to make it and then have it ready to go if you need it.

A: Uh-huh. So, so which of these isoforms was in the, the naïve vs. the memory cells.

I: A different one.

A: Oh, a different one. Okay

I: The one I'm talking about was one that came up right after activation.

A: Oh, ok

I: So there are some proteins where they're poly-ubiquitinated, but then you activate the cell, it stops the poly-ubiquitination. It comes to the surface. MHC class II is like that for dendritic cells. Out in the tissue they're immature, they don't need MHC-II. But then when you activate them, they put on MHC II so that they can then move to the T-cell areas to stimulate them. And that is also controlled by poly-ubiquitination. … So it's a mechanism that's been seen in other cells. I mean for other proteins.

A: Right. Um. And. It sounds like you had, you know, a lot of RNA data, protein expression data, um, can you talk a little bit about you know, how you analyzed the data?

I: Oh. Um. Well, we did western blots for proteins. We did northern blots. And basically you try and use programs that quantitate. So you measure the intensity of the bands and you quantitate that, and you try to have some controls to quantitate for protein loading or for total RNA so that it's more meaningful. Um, so that's how we did the quantitation. We also did, um, quantitative PCR.

A: Ok

I: So that was another thing we did, and we did you know with appropriate controls. So that's how we did the quantitation.

A: And so your RNA, that was by quantitative PCR, or that was by, were you doing sequencing, or?

I: That was really quantitative PCR.

A: Right, you know specially the things you're looking for.

I: Right right.

A: Um, okay. So other than the, you've already mentioned the challenge of the probe. Were there other particular challenging aspects of this project?

I: Well, I had mentioned the probe. I also mentioned that one of the isoforms wasn't expressed. That's a second challenging, okay. I think the third challenging was that, um, uh, when you add your, um, gene to human T cells, you have to stimulate them and add cytokines to keep them growing

A: Ok

I: And I think, um, at the time. And then we restimulated them to look at the functional effect. Cause you have to stimulate them to add the isoforms. Because resting T cells don't take up genes.

A: Oh interesting

I: We had them on retroviruses. They had to be multiplying. So we had to multiply them first, then we had to get them to rest, and then restimulate them. And at the time I think our cytokine concentrations were too high. So we saw some effects, but not as dramatic I think if we had kept our cytokine IL2 for proliferation lower. It's just that people had. We saw it in the literature, and um, so we used that, but I think in hindsight, we probably should have tried some different concentrations to see if we would have gotten better cytokine concentration after restimulation if we'd kept our initial cytokine low, a little lower.

A: Uh-huh

I: So that was a challenge. We didn't get as dramatic effect as we thought we were going to get. But I think because our system wasn't optimized.

A: Right. … And so

I: So we got some effects, but not dramatic

A: Right, right. So, is this something where you're still working on it, or that's been published? What's the status?

I: It's already been published.

A: Okay, so how did you know, or how did you decide that even though you had not as big effects as you wanted or as you expected, how did you decide that it was still enough?

I: Well, we saw a difference. So we could say that there's a functional difference here, in terms of the impact on cytokine expression after activation. So we could say that, but we might have had a more dramatic effect or maybe seen some other effects if the system had been a little bit more optimized. And then over time I noticed people were using certain combinations of cytokines so the one we were

using was less. So that they could maintain the clels better. So instead of proliferating there were cytokines that would affect survival. So the combination of cytokines had changed in terms of how you would maintain the cells.

A: Interesting.

I: So that was an optimization that at the time we did the experiments we did not use.

A: Right, right. So what are the like, implications of your findings?

I: Um, our implications of the findings are that um, these isoforms fine tune the T cell responses, and contribute to, um, the different properties of an activated, a naïve and a memory cell.

A: Uh-huh

I: And that they've um, memory development is a little. Is an important aspect of vertebrate immunology. And the mice doesn't have. Don't have these isoforms

A: Oh

I: They're only in human, and we found them in great apes.

A: Huh

I: And ..vidians. so the isoforms were there, but they're not in old world monkeys.

A: Interesting

I: So they, they're a relatively recent evolution. And so, um, so we think that their function is to fine tune the T-cells.

A: Okay

I: That are most appropriate for the cell types. And the therapeutic implications is that people are using T cells for immunotherapy. They're expanding them in vitro and then putting them back into patients. And they're looking at different sub-populations, and they have different manipulations. So T cell therapy is a form of immunotherapy now. So being aware of what isoforms the cells are expressing and how that might affect the function is relevant

A: Yeah

I: So that's where I think it is, the significance of it.

A: Uh-huh, yeah. Um. And let's see. Looking at my list of questions here.

I: I have to go soon, so.

Ag: Oh, okay. So kind of an overarching question that we've had, or that we've noticed is that people use models all the time, so I was wondering if you could say anything about how you used models in this project.

I: Um. Well, we already had a model of the T-cell receptor interacting with MHC and CD8 is a co-receptor. So we already knew that. We were really just building upon a current model of what's known. So I don't think we created a new model.

A: Okay, but you were building upon a model.

I: Yes.

A: Okay. Yeah. So this was very helpful for me, and thank you very much.

Computer science, industry

a: So we're I'm interviewing you, as part of a project to identify how experts think as they solve problems in their work. And our goal is to identify what students ought to be doing and ought to learn in order to improve education. And so what I'd like you to do today is think about a problem that you solve and can talk about in reasonable detail and just walk me through everything you did - all the steps you took all the decisions you made along the way. I can guide in more detail questions as we get going.

C: Sure. So I think what I'll get I'll go with the sorts of problems that I usually feel most accomplished after getting them done. And generally, highly frustrated during the process.

a: Okay. Sounds good.

C: Yes. So we've got a couple of systems at work that basically deal with you know big data flows and so I'll try and describe the context, briefly. If you think more context would be helpful, let me know.

A: Ok

C: Um, but yeah, we basically if we sell a job advertising. We charge per click. We've got a lot of conditions under which you know a click on a job is not chargeable and then we have it different customers have different amounts that they want to spend, which is kind of a budget camp. And so we aggregate all this information together. And kind of re-figure remaining budgets and things like that ideally on an every 15 minute basis.

A: Okay,

C: And so it, we, in order to accomplish the speed. We have a lot of things that are kind of highly optimized, but it makes them a little harder to understand at times. Which can make yes, it can make figuring out what's going wrong when there is a problem of some sort, challenging. So yeah, having a hold on getting a whole bunch of.

Generally speaking, you know, we'll see a problem every now and then, where you know some customer is, you know, we're delivering past what their requested cap is. I'll go with an example like that and to generally speaking, yea, It's kind of a giant series of things with all of this unique and rapidly changing data and so trying. It's very challenging to use a lot of the, you know, what I would call normal research. Yeah, stuff that we would use for a lot of other problems where you kind of try and isolate it and get things into a static state and then you can kind of repeat the problem over and over again until you understand it.

a: Okay.

C: Yeah but but since the data we're working on is always changing. It can be more of a challenge to understand what's going on.

a: So can you say a little bit more about how the data is changing what you mean by that.

C: Yeah, so we've I guess the two main ways it changes. Is one clicks keep coming in. People keep looking for jobs. So the overall body of data is changing. And the second thing, which kind of goes back a little bit to what I said about how we've got different rules for how a click is or is not chargeable

One of the really big things is, there's all kinds of crawlers and bots on the internet that are going around harvesting data and hitting links.

A: I see

C: And so we don't want to charge our customers for those. Some of them are really easy to recognize some of them. Some of them Yeah, we kind of watch for non-human like behavior. And so sometimes you know a crawler can yeah essentially do a whole bunch of clicks on jobs. Before we recognize it is a crawler

A: I see

C: And then once we recognize that we go back and say, Okay, all those clicks that we thought were okay are actually not okay

A: right

C: so that actually kind of changes the recent past, in addition to just having more data coming in coming into the future.

A: Okay.

C: And so. Yeah, I guess where I usually start with one of these one of these problems. Is it. Yeah, kinda just track trying to gather as much of the data is I can together. So it, it's figuring out exactly what symptoms we're seeing. Trying to, you kind of, looking for patterns there. Usually also look. We'll get a report of, you know, one customer having something funny. Once we kind of figure out

What's going on there. We look and see if that pattern exists anywhere else, also. Since since finding multiple things, multiple instances can make it easier to understand what's going on.

I think, you know, ultimately, I go through a whole lot of different steps with the goal of kind of systematizing the thing. It's sort of kind of, trying to figure out what the. Uh. What the mathematical function of the system is

a: Okay.

C: Yeah, the that essentially it's a sort of simple, we take all the clicks for a certain customer and they've all got a price and we add them up over time and figure out at what time you know just one of those, you know, hit a cap and we should stop delivering or. You know, or should we put some budget back in because we decided, one of the clicks came from a bot. Um… And I guess when everything's working right. It's, yeah. It's that simple. But, but trying to figure out, trying to think of the … best way to put it here and I'm trying to avoid using too much jargon. Also, if it’s one of those

a: You could go ahead and just use the jargon and I’ll ask you if I don’t understand.

C: Yes. So in terms of kind of figuring out what what's going wrong in the system. One part of it will be just kind of acquainting myself deeply with what the. What the system is supposed to be doing and how it's working. I’ll do a lot of kind of just tracing through code, do a combination of. Yeah, kind of working on paper and looking through source code just to kind of track. Yeah, track a large number of variables

that are changing through this process as it runs and to kind of a matter of, you know, maintaining or tracking what the state of the system is at each point and trying to understand, you know, where something's yeah. Oftentimes, for some things, initially going wrong that you know end up causing the problem we see at the end.

A: And so are you doing are you doing this in real time as new clicks are coming in and you're or is this like in a test scenario.

C: So at the, at the very beginning of our process. I will usually be, you know, looking at yeah live data or near live data anyway. While I try and come up with theories for what what's going wrong. We do move on to trying to duplicate it in kind of a closed test environment. You know, which, depending on the complexity of what the problem is, can be easier or harder. That's pretty much always the goal is to ultimately figure out the, the simplest possible case that can demonstrate what's going on. So,

I guess, I start, a lot of the time with making sure I'm familiar with, with the system I'm working on. And then in this case, at least you know, looking at a whole lot of the data to try and see what looks right. What looks possibly questionable? Which can, does, lead to a lot of kind of dead end paths, where something that seems like that might be kind of funny. And it turns out it's actually fine.

A: huh

C: The yes. So I think is one part of it is just figuring out how to, I guess, to compartmentalize the information I think I said I do some work on paper on the side of the computer and also trying to just kind of systematize everything. It. But I guess one thing that I feel like is usually the point where things start to get easier when I'm dealing with something is when I'm. Figure out kind of my whatever my mental system I need to, to compartmentalize different pieces of the puzzle,

A: Ok

C: so that I can kind of not have to actually try and track all 20 or 30 or 40 variables all at once, but I can kind of say these are together. And in this part, I can ignore this one set, or I can know that this set is kind of going to be static for this portion of the process. Yes. So I think of it, in some ways, almost, you know, like a, in mathematical formulas. You'll often have formulas that are made of multiple other formulas.

A: Uh-huh

C: And so, if you've got, you know, like f of y of x, you started just assume that y of x is, yes, some value, but you don't always have to worry about exactly what's inside there. Yes. So I think that's one of the. One of my big things. Is it just figuring out how to. How to organize things in my brain so that I can track what's going on well enough without either. Yeah, having to continually restart because I lose, lose some piece or other. And that I think is pretty true kind of for almost all. Almost all the stuff that I work on and on the, I guess the other problem solving end in terms of you know, doing the programming as opposed to debugging part of computer related things.

A: Mhmm

C: It's a matter of figuring out how to separate things out and compartmentalize everything so that you can get the things you need, but you don't have to worry a lot about things that you don't need at every point. So going back to the kind of de-bugging equation I was discussing here. Um …

a: So you were talking about, like, you know, you're trying to understand the code and, and you're watching the data in real time and you're sorting it out in your head and figure out what you can compartmentalize. And so then, then what?

C: Yeah. Yes, so it's some level there's just, I think some amount of, you know, just trial and error in terms of kind of trying to, you know, look at the known anomaly and figure out what could have. it. What would have to be in place at the step before the end in order for the end to end up like that? And then kind of back it out, you know, one more step. Okay, so what needed to be happening at the step before that in order for you to step, you know, and minus one to have ended up in one of those one of those states. Which I guess that. That's also a little bit in the kind of compartmentalizing and formalizing. Yes, sort of angle. And I feel like there's probably some sort of word out of

A: (laughs)

C: mathematical proofs for that sort of operation it. Yeah, but basically figuring out where. What the system's doing wrong and what needed to be happening in order for that to happen.

a: Uh huh.

C: Then you repeat back until you find the get the root cause of it.

a: And so then what do you do once you find where it's going wrong?

C: And so. Then we got kind of the. Sometimes the solution becomes obvious which is always nice.

A: laughs

C: When a when I guess the two other you know kind of general things that can happen is you know. One, either there's just not a really obvious solution or it's kind of a question of just if I change this, it changed the way that this value works or change, you know, what the value is. Does that have any does that have any negative effects on a different part of the system. So there, I think there is one common thing that can happen is if somebody put some some value in for you to use for some purpose and then somebody else later on sees it there. And thinks, it's what they need for their thing and if those two people aren't both yeah aren't both right.

A: uh-huh

C: then you can end up in a situation where something else may actually be relying on the buggy code.

A: Right.

C: Yeah, and and so at that point is that you get, I guess kind of more just into the general design thing of figuring out how to make the changes that need to be made without negatively impacting other things which is some of that is just testing. And seeing what happens with the change. Um. Yes, some of it will be kind of abstracting things out. And, you know, possibly adding kind of layer in somewhere if

there's some value that we need to change for one case. But in other cases, it shouldn't be. It shouldn't be changed, um,

A: Mhm

C: Yeah, then that Yeah I would look at you know whether there's some, some kind of a transform we can apply where appropriate. Yeah. It's a matter of, of the value still being essentially correct but yeah. Like a contrived case. Yeah. Imagine we needed a different units in some other situation. Which I suppose with with clicks like current changing currency. Yeah. is a valid thing. So from. Yes, so having found what the cause of the…. having found what we think the error is and working on how to fix it. Yes, so the.

I guess the probably the more interesting thing is like when it, when the fix isn't obvious and that kind of also ends up being a question of figuring out how to understand the system so that we can get the right values in on the front side. So that everything flows through and gets the correct result at the end. And I feel like a lot of it. There is. Yeah, also kind of understanding. Or I guess learning. Yeah, how, how the system all works together.

A: Mhmm

C: Keeping. And working to keep the components separated enough so that we can say this thing does this and it, yeah. needs this information. And it produces this other information. Without having to yeah ideally worry too much about what's inside of it. Which I guess is. Yes. So there's a lot of abstracting things out. Or I guess really figuring out what should be abstracted out and what they need to actually know the details of or need to worry about the details of at any given point. I'm trying to think about how… Like what I usually go through to try and decide what

a: So is it. Is this something where you would be allowed to actually talk through a really specific case to go ahead and get into the get into the weeds and Because I think that might help like instead of just thinking, kind of, generally what you usually do think about an a really specific instance of doing this process.

C: Yeah, coming along with the train. … Through something that's recent enough that I've still got a good handle on it. Hopefully,

a: Sure. Of course.

C: And thinking in particular about situations where the solution wasn't immediately obvious. Okay, so. So here's one that I think I can explain reasonably quickly and the solution ended up being interesting. I'm not 100% sure this if it will demonstrate a good, like a systematic teachable approach.

A: that's ok

C: This, more on the like just we kind of banged our head against it until the answer miraculously appeared

A: that's okay

C: Yeah, so we've got this situation with it with budget caps and then advertising orders. And within our system is. So you have kind of your chief budget that's all of the money that you may spend on advertising a large portion of your jobs, then you've got individual orders that are kind of. They draw budget out of this main budget.

A: Ok

C: We allow there to be caps at both levels. So you can say out of this main budget per month. I don't want to spend more than $1,000 and then I've got a couple of different orders. Yeah, and maybe one of them is, you know, some jobs that I really want to get filled fast and I put a higher cap on that and some of them are less critical roles. So I put a lower cap on them.

And so within our system as we're going through and figuring out what clicks fall within, within budget on an order. So yeah, a click on one of your jobs has occurred. We have to go there. It basically has to be, you know, falling under the cap of the main budget and also falling under the cap of whatever individual order it's on. Because. Because there's multiple orders per overall budget. We. There's situations where you may be within cap on an order, but the budget, the budget on its in its entirety is actually over cap.

A: Okay

C: And you can actually have, you can have the same thing happen in the other direction. As well.

A: Right.

C: And so then the. When we were initially conceiving of the system. Yeah, we were thinking to have things be flexible such that if you've got multiple top level budgets that you could move an order from one budget to another. And as we were starting to work through that and build that, it became apparent that in that too. If you are moving in order from one budget to another, you had to do this check of if this click occurred on this order and budget combination yet, then that could deduct the value from each of their caps.

But then if the ad or had moved. It. There's a situation where it basically became. It made things complicated for figuring out how to combine the caps. Or not really combine, but how overlay to caps and the budgets. And orders such that for any number of moves we could always figure out how many iterations of this process we needed to do in order to come to a stable state in terms of budget value. But it was kind of it was a bad process or a bad thing for kind of all the automatic processing.

A: Ah

C: Because it was one of those things where, like, if you move in order from budget one to budget two to budget three and then back to budget two you could end up in a different scenario than if it went from one to two to three to four.

A: Ah okay

C: Even though it was that, yeah, it's the same number of moves.

A: Right.

C: But there were kind of some feedback cycles in the system and so that it it basically came down to a situation where it was going to be. Yeah, I guess I shouldn't say unpredictable. Because for any specific scenario we could figure out how many iterations we needed to do in order to get to a stable state.

But, but, but there is a scenario where you know like if one person did a whole bunch of moving around because they were indecisive or something like that, it could kind of cause the whole system to take a very long time to actually figure out the answer.

A: I see.

C: Um. And so with that, we spent an enormous amount of time trying to, you know, figure out, you know, what's the math that will make this work? Or you know what some sort of a simplifying formula.

And trying it kind of what would happen if we reorganize the way the system works and looking at a bunch of, kind of some simple, some really complicated, fixes for it that we're all just not really satisfactory.

And what we ultimately came up with was to. You know, one, kind of cut the problem off at the root and just say that okay, we're just not going to allow moving orders from one budget to another so that we can't get into this scenario of. Of being uncertain how much processing we need to do.

A: Uh-huh

C: And so that. Yeah, I guess from the. Yeah I don't know if this will be as helpful for the like a computer science type, problem solving, but yeah it ultimately kind of turned into. It helped to reanalyze it as a business problem. And rather than you having a technological solution we set that rule in place that you can't move an order from one place to another. But then thinking about why somebody would want to move an order from one budget to another probably would be to make more or different money available to it.

A: Mhmm

C: And you know, we do have the ability to move money from one budget to a different budget. That can handle a certain part of that. And then the second, or the flip side of that is we ended up also building in kind of a system so that you could duplicate an order and run that on a different budget.

A: Mm okay.

C: Um, and that really, I guess was just kind of a situation of kind of bringing our heads up out of the immediate work and you know figuring out kind of the. The other solutions that were available outside of trying to do something that was strictly highly technical

a: Uh huh. So when you were talking about all the solutions that you were thinking of that you decided weren't satisfactory. How did you. Can you talk about how you were testing those or how you decided that they didn't work?

C: Yeah, um, And so you know what we, basically, uh, I don't think we ever actually ended up coding anything up for that. You know, but it kind of just a whole lot of us sketching things out on whiteboards, and you're kind of running through the model of the system. With the goal of. We had our. We had the

goal that we want to be able to come to the answer of how much budget is remaining on all of these on all these components. Yeah, in a predictable and ideally small number of variations.

A: Uh-huh

C: And I think where we were considering a small number to be like, not more than three passes. um, which that was really just no strict technical reason we picked three, just seemed like a good number.

A: Ok

C: And so we kind of had our, our goals that we needed to meet for it to set. that we wanted to satisfy. And then kind of had this system model for how all the math works out. And it was. Yeah, I guess some, some of the options was essentially kind of replace this part of the model with a different piece that did that job a little differently. Um. Yes, sometimes it was a matter of how we, you know, change the inputs in and out in terms of, you know, could we … slow things down a little bit and work with a larger time period's worth of data so that we can get. So there could still be a, there could still be switches and there would actually be more switches, but there wouldn't be a. Trying to think what the right terminology would be

But, but, kind of, if we're doing the work in batches. There would be fewer batches, in which an individual order was likely to have moved.

A: mm. interesting.

C: If we just have larger batches that. All that didn't end up really solving the problem. And I think it with that. For, you know, for the individual changes, there's kind of the idea of it taking our system model. Yeah, saying, Okay, how will it change if we, how will, how will it behave if we make this change to it? And I think just to some degree, there can be kind of a gut feel as to should we test this requirement or test that requirement first? One of them might be easier to test or one of them might be, the more likely one to to fail.

A: Mmm

C: If we've got a you know a number of things we need to have satisfied, then figuring out which one is easiest to test failure first. Is Is helpful. All that being said, I suppose we do also have a tendency, especially when we're kind of a exploring different alternatives that you kind of want to look at how each change would behave against all of the criteria. Yes, so against the, does it get us to a strictly finite and predictable number of passes and does it all fall within the three pass restriction?

a: And so you mentioned you're comparing it to or you're thinking about how it would function in your system model. Can you say a little bit more about what a system model means?

C: Yeah. So in this case, it is essentially a flow chart, which are not really so popular. But basically kind of a. Yes, set up or at least a conceptual flow chart. Yeah. But the idea that we have, You know, a certain number of components that are inputs into the system that they move into this box and this stuff happens, which then you create some kind of output that goes on to the next step in the process.

And we've. Yeah, there's traditional things where, at some point, we may go one way or another. And like I say, for this particular one we. The model was kind of purely conceptual way in a sense that. It was

an easy situation to just represent as math, without having to actually build all the components. Yes, so we can essentially say you know, what happens if we change the math here? Or what happens if we reorder these two parts of the process? And so yes, so the. I think the modeling aspect, is the compartmentalizing the systematizing things where. Yeah, we basically have you have this whole process that the system runs through and. If the. Trying to think. Yes, so we got kind of the, the process that we've got in mind. And then we're trying to figure out how to. What we can do to make it behave more the way we wanted to

A: Mhmm

C: And so it's. Yeah, I guess, largely. Yeah, we go through and try and swap this piece out for something that did that job in a different way. We do kind of at the more general level. Yeah, the. Yeah, it's not entirely uncommon to just actually kind of build say maybe not quite a prototype, per se, but you're writing code that will let us test things out.

a: Mhm… And so with this. With this problem like, how did you end up deciding that you wanted to, to solve the problem in the first place? Was it. Yeah. How did you, how did you start?

C: Okay, um, Let's see, so that was essentially kind of just a. Yeah, basically just a business need. The system that had been doing this job in the past was both getting it was not scaling well as the business grew so it was getting slower and slower, and that really was not doing this job well enough. And then we also wanted there to be a lot more flexibility in terms of allowing customers to advertise more granularly and kind of arrange their spend in more in more complicated ways

A: Mhmm

C: Yes. So that was kind of the, the very start of it. You know, one of the pieces. That was new, was the introduction of this budget model that It. Yeah, our previous system was kind of a - you make one purchase and then your stuff runs on that purchase and then when that's done, then you make another purchase. You create new orders to advertise your jobs against that new purchase. It and it was a challenge. People had a lot of manual workarounds for doing things. Like some big customers do a lot of hiring you know over the summer or at a specific time of your hiring.

And yes, so there be a large amount of very manual workarounds for trying to, you know, purchase all their advertising at the beginning of the year and some of it for the, you know, April, May time when we're hiring for our summer workers and things like that. And to be a part of what we were building in with the idea of having this budget model was to allow multiple purchases to potentially go into the same budget, but also allow all, a single purchase to be apportioned out so that somebody can reserve their money. The advertising money, they want to use to try and hire new grads in June.

a: Uh-huh. And so the specific aspect of moving the budget was like that was a problem within the larger problem of creating this whole new system?

C: Oh, yes.

a: And you also had mentioned cases where there's like… A bug shows up in the, um, where something screwy happens with with some client. Um, how do you find out that something screwy has happened?

C: Okay um well ideally. In the ideal scenario is where we've set up the right monitors to detect such things. And we get alerted by our own systems. Yeah, the some some value is out of balance or is it an unexpected or the. Yep. The value, the value is not right in a way that we predicted it would be a problem if the value was was wrong.

A: uh-huh

C: Yes and yes. So that's the ideal case. We also get, you know, information that comes in for our customer service or direct from customers. Yeah, where somebody's noticed something that they don't think it's right at any rate. Which yeah sometimes it's actually not right. Sometimes it is and how things are actually supposed to work.

A: Uh-huh

C: But, but, yeah, so that's really kind of the main. I suppose the. The third area that that's kind of in the middle is you know me, or somebody else on the team is are you looking through either the data or the code and notice something that just doesn't look right. Which is not as nice as having actually you know predicted where something could go wrong.

a: Right

C: But, but a little better to catch it before somebody before somebody who's affected by it notices.

a: Right, right. Um, and you were, you were also talking about, kind of, in general, if you're trying to figure out how to fix something and you make a fix that. Are you making it… And then that's going to affect everything everybody too, to or like what's the… How does fixing it end up happening?

C: Um, So yeah, I think there's. Yeah, I guess, always a balance to be made between making a kind of smallest change possible. Is sometimes preferred because it's least likely to cause any other chaos.

Although there's also a. Yeah, things can happen with systems that are big enough that if you start doing too many smallest changes possible without considering the larger system. Then you suddenly have all these, you know, like the Lego pieces that aren't quite shaped like Lego pieces anymore. They're all a little different and stuff doesn't. Yeah, it starts being really difficult to make system wide changes.

A: uh-huh

C: And so yeah, I think the the balance for, you know, is this a scenario where we want to make the smallest change versus should we do something more systematic? yeah it is partly just a question of what the actual Yep what the actual problem we're solving is. Yeah. And then sometimes also a matter of how quickly do we need to actually have a fix ready? In the sense that the smaller. The smaller usually is. Is a little bit safer, but might not be the right long term decision.

A: Mhmm

C: And I guess that they're also is some. the scenario of figuring out a small quick safe fix, while also figuring out what we should be doing over the next, you know, some period of time. To kind of keep the system as a whole, flowing fairly smoothly. And so yeah, I guess. There too it actually makes me think of

another kind of interesting thing we work with the times. Is kind of so called data migrations where we want to change the meaning of some value through the system.

A: Ah

C: Yeah, but the system had to keep running while we're doing this.

a: ah. Okay.

C: Or adding or removing data. And I think there. Often is really just a large amount of it playing out scenarios and. I think the so the hardest part usually is just figuring out everything that you need to be aware of. I'm trying to think about. I think they're usually the best bet that I've got is just to go test thoroughly and do it over and over and over again in testing environments.

A: Okay

C: Until. Yeah, I've got pretty high confidence that I've identified everything that could be affected by making this change. Yeah, trying to kind of trying to think of the. Like, overall, what I would get trained to tell somebody they. Or what approach I would tell somebody they should try and take for that kind of problem, which. Yeah, I guess, is essentially kind of just a. Yeah. tracing it through from start to finish and finding all the touch points.

A: Mhmm

C: If we, I guess, a similar thing that we that I did just kind of early spring through the early summer was getting our system kind of rebuilt to support multiple currencies. We previously started in [location]. Everything was US dollars.

A: Uh-huh

C: Turns out, much of the world doesn't do their day to day business in the US dollars. And yes, so that was kind of just a matter of. First off, we had a good. Yeah, it was pretty easy to find all the places where you know dollar values are represented in the system. Which was a thing. That at least is kind of Everybody knows where the money is.

A: Uh-huh

C: So Actually finding that it wasn't a situation where it was like, well, what if there's some currency being used in some other part of the system we haven't thought about. But there it kind of starting with all the places, we know where we use dollar values. And then going through and figuring out, you know, where is the appropriate way to do currency conversions, if needed, or. Yeah. Are there some scenarios where we don't actually strictly need to do currency conversions, because it's essentially you know just passing through.

A: Right.

C: And I think, yeah, I guess, at some level, it's. Again, just kind of a systematizing and figuring out you know what things I need to pay attention to in the process and keeping the others. You know, sort of the larger segments that I can just think of as a whole, without worrying about the details. I'm trying to think

if there was anything really interesting that we went through. Making those changes. … Yeah, sorry, not anything that I can think of at the moment.

a: Okay, that's fine. So I'd be I you basically answered all my questions. I have a list of questions and I didn't need to ask a lot of them. So It was great. And I'm wondering if you have. Do if you're thinking about a new hire or a trainee, what sort of difficulties, do you see in in them in their problem solving, or difficulties that they have in their problem solving?

C: Okay. Let me see here. Yeah, I think one thing that I do that I feel like I've run into fairly regularly is people who I think are very. Kind of too focused on the immediate problem at hand and not,

not generally considering you know whether this little problem right here is potentially a bigger thing in the system that should be fixed. Or already should we be rethinking the way we do this? You do this thing, rather than just making one fix here?

A: Mhmm

C: And I think yeah, that probably I think scales, a lot with just general experience level and having your. Having run into enough times when I've, you know, made a small fix and then get a very similar small somewhere else, and a very similar change somewhere else. And then at some point, suddenly realized that actually instead of like doing all these little things I should have actually been Yeah, thinking about like how do I or the team or the company conceptualize this particular process or product or thing? Yes, so. Yeah, I think just the matter of kind of figuring out how to, you know, lean back, and like you know be working on a certain thing.

Like we're working on a certain thing. And, uh, but being aware of, kind of the, the somewhat wider area around it. Not necessarily that somebody, somebody needs to like consider all of everything.

But keeping, keeping an eye on you know what the immediate neighbors are kind of basically. That Yeah, one of the places where that does get. Or I guess one of the reasons I think that it is a little bit challenging sometimes within the computer science software engineering kind of world is that there. Yeah, that there's a lot of places where you can work and you're actually are working on a very narrow, a very narrowly scoped part of something.

A: Ah

C: You don't actually have a lot of Interaction with other components and you were. So I guess yes, speaking as to get my my specific challenges with new hires or hiring people. You know, the group that I work with is more kind of central to a lot of things and we provide a lot of components that are used by a lot of other people. And we also consume a lot of things that are built by other teams. And so, you know, we have a higher need and then some places, some teams anyway, for Keeping. Having a higher breadth of knowledge. Knowing what we do, but also knowing what some of our What, some are neighbors are working on.

A: That makes sense. All right, great.

Earth Science Industry

A: So what I'd like you to do is think about a project you've worked on. And walk me through what you did. So the steps you were taking how you started on it and what decisions you were making along the way. And I'll ask more detailed questions as you go along if I feel like they're needed. Um, but yeah.

E: Okay, um, One. Okay, so the thing I'm thinking of is, I had an exploration gold. I do gold exploration and copper and a few other things. So the project I'm thinking of is a place called [location], which is near [place]

A: Ok

E: [description of location and gold trend it's in]. So I got hired to do this project. And someone else had already developed some had done already done some mapping. There's been previous work there already. Someone else was assigned to do the task of choosing where drill holes were going to be. So this project was at this kind of advanced far enough that it was drilling and my task was going to be supervising the drilling and logging the core and developing a new model.

A: Okay. And can you elaborate a little bit on what you mean by model?

E: Um, A. Take the data you have, and use that to. Decide what you think, sort of where you think the the rocks that the stratigraphy is, I'm sure you know this word. I don't know if all the other researchers know this word.

A: That's okay

E: Where the rock units you have both surface mapping and you have previous drilling and now you're going to have new drill data. So the surface mapping tells you where everything is obviously on the surface and the drilling tells you where the rock units are in the third dimension.

A: Uh-huh

E: at different angles. And so you use that to kind of extrapolate between the points or interpolate between the known points to say, okay, I think this unit is there and this unit is there in three dimensions. And I therefore think the gold is going to be in such a such a place in three dimensions. And so the model is where you think in this case where you. What. Both the geologic units and the gold will be. And so a decision about where you want to drill next, or farther along a decision about where you ought to be mining.

E: Ok

A: so model is what you expect the distribution of rock units and the gold to be.

E: Okay, great.

A: So we had some some data from previous drilling. We had some of the previous the. The manager, whose job it was to pick um drill locations had. Okay, so here's the went slightly wrong thing that they they picked drill locations. Okay, I'll say he because. But I'll be correct and say they. They had the drill locations at a place. It turns out he pick them from the map from where his map suggested it ought to

be. And it wasn't a fine enough grained map and the places he picked the exact. He he gave us coordinates and UTM coordinates do you need me to explain UTM?

a: I think that's okay.

E: Okay, so he, and but it was too coarse grained. And so when we went to the location. It was really awkward location of how to set up the drill and what angle the point the drill. So I had to look around, where he expected the gold to be and where the drill was and say, Uh… That's going to be that. Here. Let's move the drill over to here.

A: Interesting

E: And make sure it goes and estimate what the angle should be to hit where he thinks the gold would be. um, how I did that. Well, I walked out on the ground, which is what he had skipped. Excuse me a minute.

Um, so there was there was. Some of that is fine tuning exactly where the drill should be positioned and exactly what angle it should have with the drill and the drillers there.

A: Uh-huh

E: And then. This, this, the drilling produces rock core, which is a cylinder rock, as opposed to chips of rock, which is very nice for doing. You can you can understand what's going on a lot better when you have core, although it's a lot more expensive to drill. So I sat. So that was part of it. Um. Part of all this involves also finding a location in town where we could take the core to after it came up out of the ground and

A: Interesting

E: So, This is not something you necessarily think about when you're doing science, but where are you going to put your, your data. Physic. When your data includes physical stuff like rock. So then you can look at it and then and analyze it as it needs to be done. So we found nice. A an old what had once been a garage. They have a lot of old antique mechanical things, and the old antique tools and we rented it out and were able to set up tables and put that out and I was able to hire as an assistant, a young woman in town who could help me with cleaning the core and taking photos, which was also a task. So that's another kind of part of problem solving is finding the right people to help you.

A: Ah

E: Because it's never all by yourself. And in fact, in some senses. I was a part of someone else's problem solving, because I was the right person to help do that.

A: Right

E: Um, so. The drill. We picked up we got the drill core. We got the rock out 10 feet at a time and the drillers put it in the boxes and we hauled it down the hill to this area and then had to then the next step was a logging it, which is to make a. I know you know what this is for the purpose of the description

A: Sure

E: Make a description on geologic description of what kind of rock it is, what minerals are there, what the original minerals were and what the interesting from the point and what interesting minerals are from the point of view of gold exploration. And also a description of the structures in the rock that. The texture. If there's a… Some sort of grain in the rock or if it's isometric equal in all directions. If there's bedding or shearing or something like that. If there's fractures measuring that and. And then once you've described it all sort of make an interpretation that says, I think this was fresh rock. I think this was altered rock. I think there is more alteration farther up and farther down, to the left and right, that sort of thing. And then send it off to the assay lab and you oh you also make an estimate of if you think there's gold there how much it might be

A: Ok

E: And then send it off to the lab and then they. Tell you how right or wrong, you are

a: So do you end up sending all of the course to the lab or just ones that you think there's something interesting.

E In this case, we send the entire length of the 10 feet, but we cut it first and only. Cut it, cut it, how to describe this? Wo that you, you have a half cylinder

A: Ok

E: So it’s round on one side and flat on the other

A: Right

E: Half cylinder and send that half cylinder in. Oh, you also have to decide where to divide the sample sort of. At well 1.5 feet or 12.5 feet or wherever you have to the length of that. So how much. There are constraints about how much rock they can put together into one sample or how little rock is geologically significant. I guess that should be included. If you get a very, very if you take a very, very small sample and it happens to come out very high grade. It may or may not be representative of anything interesting or useful.

A: Right.

E: Because in the end, when you're. Assuming it turns into a gold mine, you're taking the rock out a loader bucket at a time. Right, so very, very small sample is not useful even though it might be pure gold, but

A: Interesting

E: So you need to understand the representativity of each sample that you have chosen. And so this company wanted to analyze the entire core, which is a good thing. Geologically there's a lot more interesting, more. You learn more that way. Some companies are short on money and only want you to analyze some things that are most likely to have a lot of gold in them.

A: Okay

E: And then the part you didn't analyze do you assign that a value of zero, do you assign value of unknown? What what value do. In this model, you're going to make later on. Um, zero is not the same as very low.

A: Right

E: So that's a decision. Fortunately, I didn't have to make that decision in that for this job. Some others one does have to. And. Um, I guess under other things is when when you run into trouble drilling and the the drill doesn't make progress, you need to make decisions about do you keep going? The driller will tell you what their best estimate is as to how to continue making progress, and you have to.

Here's where the money comes in. Well, it'll cost this much to continue or not, is it worth it? Or we're really stuck, and it's not going to continue under any circumstances. Or if we try again. Maybe we will.

A: Ah

E: And I guess. After all, of after we had our first hole with. This was a 10 hole project of that I think three got to the entire planned depth, um. I can't remember several others, we drilled far enough and it wasn't necessarily the planned depth, but I decided we had as much information as we needed and we stopped the hole

A: okay

E: And a couple others. There was just too much trouble drilling and we just had to abandon the hole they either. There was one, actually it was interesting that we drilled along and it turned out the previous model was completely wrong. And we were going into a completely different unit than we thought was interesting. And we just quit because a. the drill was going fine, but it was a geologic failure, instead of drill failure and we quit early for that reason, and that was one of the more interesting ones I seldom have that situation. But this was a case.

A: Huh

E: Gotta quit because the geology is wrong.

a: And the, the other ones that you thought weren't, that you decided to stop before you got to the planned depth was that were those. Similarly, because the geology was wrong, or how did you decide you had enough information from that hole?

E: Well, I talked with the boss who had the money, who was paying for it. And the other manager who had chosen the hole and we all three kind of got together and said, well, that. It's moving along. We seem to have gotten past the gold here.

A: I see

E: As farther along, we don't really think there's going to be more mineralization. So this is your estimate of how how good you think it is. We hoped that we would be the mineralization would be

100 feet long and we had it started here and it ended up being only 10 feet long and it doesn't look like we're going to get into anything more interesting, after all.

A: Ok

E: And that was sort of trusting your understanding of the geology and your understanding of how you think the gold got to be where it is.

A: Hmm.

E: And it's always, um. Your best guess and what you think is the most important thing. And there always might be more. As a geologists I often want to always go a little farther always go a little farther, but

It's better to. Here it is, is it better to spend the money on another 10 feet here or is it better to spend the money on a different drill hole with better chances? and in this case I ended the hole because it was better to spend the money on a different drill hole with better chances.

A: That makes sense.

E: And then all. Once I've made a description of all the rocks and then we got all the data back again. Then I had to write it up and I made my models by a series of cross section. So a series of two dimensional drawings and estimations. I did not put it into a three dimensional, three dimensions normally requires a computer program.

A: Uh-huh

E: And so I did not do that. I just did a series of two dimensional in that kind of. Visually, you can kind of estimate where the third dimension, what was going to happen with a third dimension. But in this case, that's, I did not do that. I'm not really fluent with any of the three dimensional programs.

A: Okay

E: And a series of two dimensional cross sections was adequate for this job.

a: And so then, so you created your, your map. And did you did you make any recommendations for them or you just gave them your model?

E: Yes, I took each hole. And I said, Okay, this hole. Each hole was associated with a certain target and so on. The, for example, the hole where we went into a completely different unit than expected. I said,

Okay, that's that that's the end of that target. No need to drill anywhere near there again

A: Right

E: Another hole that was it looks really promising, but we got stuck. Try to drill again. Another hole that looked promising, and we went the whole way but it didn't quite pan out, it's sort of. One of them, I said. Move over 10 feet and change the angle and drill there.

A: Hah

E: Another one I just said. Could be more worth trying again, if you've got enough money, but it wasn't it kind of. The target stayed at the same level of prospectivity, neither better nor worse than it was before drilling.

A: I see

E: So for each hole. I kind of advanced the target kept the target constant or decrease the prospectivity and killed the target.

a: And did you. So you said, Okay, try drilling here. Did they then go do that? And were you involved in analyzing the next round, or that was?

E: No. they didn't. Unfortunately.

A: Ok

E: And a new company has bought it and I keep telling them, don't they want someone with experience there? and then they got their own people that are doing it. So, that's what happens a lot of times, Sometimes a new company wants to get old data and old expertise or previous not that old. But previous data and they always want previous data. Sometimes they want previous expertise and sometimes they think they know better. So in this case they don't think they know better.

a: Okay. That's too bad.

Um, Okay. So was there anything Anything else that you that you did. Or have we we've completed what your what your involvement was?

E: Um, I guess we've completed what my involvement was. Part of part of it involves. I guess the same thing is when you're doing academic research read as much as you can and ask as many people as you can about what's already known or thought about the area and ask other people for help.

a: Uh-huh yeah. So…

E: I guess another aspect of it also is. Tracking the quality control of the assays, so you get numbers back. The most important thing is the numbers back from the assay lab about what what the gold content is. Also important as you get numbers back about the concentrations of about 35 other elements, besides gold. And so one of my expertises is to analyze the gold. Kind of look at the gold results and the results of certain standards that we have submitted and say, okay, is this assay

okay or not okay?

A: Uh-huh

E: And in this case all of them turned out to be okay. And I found some places, though in other jobs where we say, well, we think it's biased high or biased low

a: Uh huh. Interesting. Um, So, When you were talking about like the 10 drill holes that you had

Was that something where it was just like you drill everything and then you analyze the data or or were you kind of… Were you analyzing along the way, how is that happening?

E: Well, the, the logging of the core was happening along the way. The whole drill program was about one month, and that time. By the time I was done with logging the core. It was a month and a half. So, , um,

A: Ok

E: And or something like that. Anyway, it takes I'm logging the core as it comes out of the ground, but also doing enough other things that I don't. In this case, I did not necessarily keep up with the drills.

A: Right.

E: In the best case scenario you're done logging within a day of when the drill program is done

A: Sure

E: But yes, you're analyzing you're looking at the. You're logging results in real time as its as it's happening but On the way. But, um, what else am I saying your oh the logs. The assay results, you don't get for another two weeks or six weeks or something…. Yeah, so, um, yeah. So the it's so you're you're analyzing as it's happening and. With the logging, I'm getting some real time feedback because I can say this unit we're passing, crossing this unit or we're not crossing this unit, we think this unit might be another 10 feet farther continue or don't continue

A: Right, okay.

E: But a lot of the. There's a lot of data that's coming in more slowly. And the final report take several months after the drill program is done.

A: That makes sense. And So were there any, What were the critical decisions that you think you've made in this process?

E: critical decisions.

Um, Well, I guess in some ways that kind of how best to spend the money is the decisions. Put together with the few other people that I talked about talked with about how best to spend the money. Continue this hole or quit the hole and spend it on a different hole that was, those are critical decisions. And then at the end, the recommendations of the targets which targets were advanced and which targets were not advanced. And that the, that was the second one, the targets was more of a recommendation than a decision because then it was the client's job in the end to follow up on that or not. in this case they didn't, any of them.

a: Okay. Um, and what were particular challenges or difficulties you encountered?

E: Hmm. Um, Well, it was there were it as it turns out, there were two different kinds of opal mineralization. Opal formation and I didn't. You didn't know this ahead of time. But identifying that.

A: Hmm

E: And that was a challenge that was kind of, I guess, the challenge then is correctly identifying the rock units are going through. So that's a. We didn't know ahead of time. And so trying to figure out what was going on as the as the mineralization happened as the rocks were deposited. It was a volcanic unit. So what happened when. So fine tuning the geologic sequence of events.

And I guess that's, that's one of the bigger challenges and. Yeah, I guess, making sure your geologic decisions are right.

a: What do you mean by that?

E: oh, that that's a good question. What do I? Well deciding okay this is this. Which rock unit is it when a rock is much altered by hydrothermal processes. Um, I know you know this, but sort of, with gold mineralization of the kind that we're looking at. Typically, there is a rock. And then there's hot water that circulates through the rock that changes it into something else. And so. But so it makes it hard to tell what the rock original one was so trying to it so seeing through those hydrothermal processes and trying to identify accurately what it is you're looking at. So that was I guess the big challenge.

a: So can you actually talk maybe a little bit more about know when you're when you're looking at a core sample. Your process of how you're going about analyzing that and and figuring out what happened?

E: Um, I have before I start some expectation of what kind of rock I'm going to be looking at, and some.

And so I start with the assumption that I've got these six or eight units and the rock that I'm looking at is going to be one of those six or eight units, or an altered version of one of those six or eight units. So I get it, I look at the mineral at the texture that I can see. And the minerals that I can identify and sometimes I can't identify all the minerals. Um. And I guess. Those are the two things and minerals and the texture, the colors, and see what unit, you're looking at. And then your expectation of using those that same information. What level of alteration is this. They the terminology that I know these are familiar things to you sort of. Green schist faces, greenstone kind of alteration.

E: Argillic or advanced argillic alteration are the ones that are interesting with respect to mineralization. To gold. Chlorite is generally commonly not associated with gold, but it sometimes can be so identifying that the kind of category of mineralization there.

A: Okay

E: I already had an idea that it would be in this group called advanced argillic or high sulfidation. So identifying when you see a certain texture. Is this something that was in the volcanic rock to begin with, or did this texture happen later as a result of alteration?

A: Uh huh.

E: And how do I decide that? How that texture is distributed throughout the rock. Is it continuous through the alteration or is it only in the altered zone, for instance. What else shall I say? Certain minerals. There's a mineral called alunite that's only present in advanced argillic alteration. So if you find that, which has a certain hardness, a certain crystal form. Although, usually you don't see the crystal form. You see it kind of filling in gaps between other crystals.

A: Mhmm

E: So if you so so certain minerals. Certain clay minerals are associated with one kind of alteration versus another. And so you're looking at the color and the texture and the hardness of the clay mineral and sometimes. You know the texture includes feeling it with your fingers poking it with your sharp poker. Even you've probably seen this one before sort of. Seeing how it tastes or how it reacts with with your teeth or your tongue.

A: Hah

E: Um, So, And then even so sometimes the. You can make a prediction that it's going to be have lots of golden it that it takes the assay to be sure. None of us really has that good of an X ray eye

A: Sure.

E: Um, I guess, is there anything more? Have answered that question?

a: Yeah, no. I think you have, I think, that was great. And my, I guess I have kind of two more questions. One is, how did you. Or how did you decide that you had enough information to write up your report?

E: Oh, that's a hard one for me because I have a tendency to want to get more and more and more before I write before I commit myself to paper. So, Boy. Putting that into words. It's hard because I've tried. I just, um. Started writing

A: Okay

E: What you start, you kind of start with the background and then you. I'm not sure how I decided when I had enough information.

A: Maybe phrasing it other way, like how. When you wrote up your report, like how confident were you in, in, you know, the model that you were proposing?

E: Actually, one of the reasons I chose this one is I really felt good about the models so. um,

Maybe that's how I decided I sort of I was looking at the series of two dimensional cross sections and and the, how my, how our results compared with historic results and it just felt like I was getting somewhere.

A: Okay. …. Okay, great. Um, and so, kind of the last question I have is thinking stepping away from your work specifically in this project, but thinking about. If you were working with a student or a trainee what, what particular difficulties in problem solving have you noticed with the less experienced people and, and how do you think they might have approached the problem differently?

E: Hmm. Well, everyone has a different idea about sort of. They might. Everyone has a different idea about how the details of the of the distribution of the geologic units. Um. One thing that they might do differently as if they didn't know enough about argillic versus advanced argillic. They might mis-diagnose that.

A: Ah

E: There was another tool. It would have been nice to have called an, um, shortwave infrared spectrometer. And that helps you tell when clays are different from another one. And so one of I might have made mistakes in identifying the clay that this shortwave infrared spectrometer would have helped. Would have caught

A: Ok

E: and someone might completely miss identify the clay, or maybe I completely misidentified the clay.

Another mistake might be to give up too soon.

a: Okay.

E: Um, what else. I tend not to think of myself as… Better than other people in this and they, I hope that they would have come up with some similar results.

a: Well, sure. I guess I'm thinking well as students who. You know. Haven't had the experience level.

But I, I don't know if you ever work with students. So you might not have a perspective on what students would do.

E: I well I do sometimes work with first years I'm. Well, they might try to be too detailed. One of the really tricky things is. Understanding. How much detail is the right amount. How much is too much and how much is not enough. And I'm never quite sure. I got that one.

A: Okay,

E: um, So I have seen some people do way too much detail and it's you're just overwhelmed and you can't find the forest anymore.

A: Uh huh.

E: And so what is the important thing to record. Okay, now you're getting me think about that. Yeah. So understanding what's important to record is. And something you have to learn and. I could sort of

With someone sitting next to me, I could say, now this. I could say, okay, here this texture is the important thing to record and that part you can ignore. Especially on fractures. One of the things you're trying to understand is the general grain of where the big faults might be and where the little faults might be. So what to measure and what not to measure, um, that's something, and that might be a judgment call with other workers as well so

A: Ok

E: Yeah, that's, that's the trick and logging what record and what to to leave behind.

a: Yeah, that makes a lot of sense. Okay, well, this has been really helpful and I appreciate your taking the time to to talk with me about this. Thank you.

E: Well, you're welcome.

Electrical engineering industry (3)

A: Alright, so, um, yeah. So are the goal of our project is to have experts walk us through how they solve a problem or how they worked on a project. And to, so that we can look through your process of solving the problem and identify decisions that you made. And using those what we're trying to create a list of decisions that people make in science and engineering fields. To see if students are getting the opportunities that they need, to make those decisions in in their training. And so what what I would like you to do is to just walk me through, it sounds like the problem that you're going to talk about will be the creation of this of the system that you sent me the YouTube videos for, And so if you can walk me through kind of. How did the project come about? what steps did you take along the way? and particularly focusing on what decisions you made along the way to solve it. Is that enough context or

E: A little bit more. Yeah, I think it gives me an idea and and that's what I'd seen from the previous email interaction already. One thing I didn't get a clear understanding is what grade level are we talking about of the students here, is is this elementary, middle school, high school, college?

A: Undergraduate and Potentially even graduate students.

E: undergraduate or graduate level. Okay. [side discussion about the purpose of the research]

E: Yeah. So, so the video that I sent to you, shows a solution.

A: Okay.

E: Um, and if you listen to the whole thing. I know, I know. It goes into some technical details on power supply design and whatnot. And I'll try to abstract, you know, based on what you've told me so far based based on what I know about your own background, I'll try to use as generalized on this possible, so it doesn't get into details that you won't need. There are several other links that I sent you. One in particular is not a video. Let me go to the email that I sent to you and the one I was thinking it's from it's from a company that starts with [name]

a: Pulling up the email too

E: Go. I think it's a third link that I sent to you.

a: Okay, yeah, the [name] yeah

E: Yeah, so just to be background on [name of company], it's it's a it's a term that is used by a semiconductor component distributor called [company]. It's a worldwide distributor and. And and what what companies like [company] do is they take. they buy components from companies like [other company] and they store and forward them. So it's like a warehouse kind of situation. And they are trying to get as much training for their customers, the end customer engineers or non engineers who are who are purchasing this product, and this, this whole. Blog was created by them based on our training to them the videos, like the ones that you saw. And the reason I point this particular link to you. It is not video so you can walk through it. We can we can even use it on our call today

A: Okay great

E: walk through it right. So brief background about this tool and the need for the tool itself. If you're ready for that.

A: Yes, perfect.

E: Um, so, first of all, A bit about what power supply is all about. So all of us use in our laptops or or cell phone charging we plug in one end into the wall and the other end that goes into either the PC or the cell phone adapter and whatnot. And there is something in between that goes between the wall plug and the stuff that you plug into your, your handheld device

A: right that little box

E: that little box that sometimes it's a rectangle. Sometimes it's a cube and that sort of stuff.

What goes inside it is a power supply.

A: Okay.

E: And it's just one example of a power supply on on your PC motherboard itself. The stuff that's Underneath your keyboard or in a box that looks like a rectangular box there is something called a motherboard where, where there's a PC processor and a whole bunch of other stuff.

A: Uh huh.

E: And all of those things required various level of voltages.

A: Okay

E: To to power them. What you see in the wall is typically 110 or 240 was but it's it's alternating current AC.

A: Right

E: What most of these electronic component need is what's called a DC meaning static voltage. Say 5V or 3V or whatnot. That stuff little rectangular, we call it power brick, what that translates that alternating current voltage into is typically a 12 volt output.

A: Ok

E: And it's a single output single input kind of design, comes from the alternating current and gives you a 12 volt

a: Okay.

E: You probably also seen in the market these days for powering multiple devices. At the same time, things that have multiple USB outlets and if you look carefully, they one of them says two amps. The other one says one amp. Things like that.

A: Okay.

E: Right, so you can charge your two cell phone or your cell phone and a Fitbit at the same time and that sort of stuff. Now, those kinds of devices take in the same alternating current single input from the wall, but it produces two outputs. produces an output with two amps capability and other one to one at 1 amp capability. So on the motherboard, a similar thing is happening when the 12 volts come into the PC power supply, it needs to be split out into many, many different voltages and current levels, you know, something that's required for the PC processor, something that's required for the memory and other thing that's required for the disk drive and whatnot. Right. I mean these are different voltages different current levels.

A: Right.

E: So, a long time ago, taking back into the history of these power supplies. I mean, these have been around as long as electronics has been around. These power supplies, but some time ago, they used to be very simple. It just a AC input to 12 volt output kind of supplies and then came all this plethora of electronic components. They needed different voltages, different current levels. And back some time ago, it was so simple. That you just a few transistors and stuff were sufficient. Work with more and more stuff bo. backing on to the power supply the PC motherboards and cell phones and so on. Heat became an issue, and a simple power supply was no longer good enough. We needed something with better efficiencies. Better efficiencies and and therefore they started something called a SWITCH mode power supply. And the reason I'm mentioning this is the switch mode power supply started, you would think that it's electronic industry has been for a long time. It's first started. The PC started around early 1980s. The switch mode power supply started in the early 1990s. Until then, people were using simple. What's called linear power supplies very inefficient.

A: Ok

E: The concept for switch more power supply was there, but people were thinking it's too complex. I don't want to do it or it's too too expensive. They didn't want to do it. So in the early 1990s [company] came up with a tool on floppy disks and Excel spreadsheets and whatnot, that that made the power supply design simple

A: Okay.

E: And I think it was originally called not called [product name]. It was called power supply made easy or something like that. And it was distributed on on floppies and so on. With the advent of Internet and HTTP and web in the mid 90s and early 2000s [company] came with a web oriented version of it.

A: Okay.

E: And that became what's called [product]. [description of reason for name]

a: Okay.

E: And it's a trademarked term by [company] now [company] is a part of [other company] so [other company] inherited that [product name] trademark.

A: Okay.

E: So [product] had the origin in the early 1990s through even the early 2000, was a simple single in single out you know 12 volt AC in. I mean 110 Volts AC and 12 volt out or 12 volt in AC and five volt out kind of device.

A: Uh-huh

E: In the mid 2000s, we came to realize that, you know, many power supplies have multiple voltages and multiple currents, as we just discussed earlier in this conversation. So then came a need for how do we evolve this [product] from what it was to a multiple input multiple output or at least single input multiple output kind of scenario.

A: Uh-huh

E: But there are many ways of solving that problem. You know, do you go from 12 volt directly to a three volt do you go from 12V to step into something intermediate like five volt and then convert to three volt do you go all the way to one volt. And and depending on the scenario then depending on how you step through from the high voltage to the low voltage you could come up with different what we call [new product name].

A: Okay.

E: And that gave rise to this concept. called [product].

A: Okay

E: Right. So it allows people to play around with different scenarios, what would be. And the trade offs in various different scenarios would be size and efficiency and cost.

A: Okay.

E: You could implement it one way, and you could get the smallest possible size, but maybe you will have to sacrifice out of the cost or the efficiency. And efficiency also translates as we talked earlier into heat. If it's if it's not very efficient, then it's dropping a lot of heat. Or loss that translates into heat into your, your design. That could get hot, and you probably seen these power breaks that go between your electric outlets and your PC. Some of them get super hot and some of them are nice and cool to touch.

A: Yeah

E: That has that has to do with who designed it and how efficient, they made it.

A: Interesting

E: And of course it's a trade off right i mean. The more efficient, you're probably gonna pay more for it, you're probably going to be a little bit bigger. That sort of stuff. Right.

A: Okay.

E: So, so far, following everything. It does. It does it look like in the kind of thing that you want to talk about?

A: um yeah so

E: Any questions so far.

A: So, so yeah, I guess what I'm, what I'm interested is is hearing you then start to talk about you know what you did and it Sounds like you were involved in creating this [product name] design tool. And so what did, What did you do to design that?

E: OK, so my role in this whole thing. So I was taught this time since the early 2000s, to the creation of this tool for which I sent you the video. I was in a division of [company] called the [division name]. I was a part of the power supply power semiconductor components division. I was part of the technical marketing team. I ran a small team that was responsible for figuring out how to best sell our products.

A: Ok

E: And looking out in the industry. I didn't see anybody else that had this [product] concept that we had at [company] single input single output. You know, make it easy for the customers and we had heard it from many customers. And this was prior to me taking on the role. So the concept that I described to you from floppies to designing spot supplies on the web was there before I joined that division.

A: Okay

E: That had been created by a team of software and hardware engineers that preceded me. Me and my team, we came up with this concept called [product] and and my role into it was the recognition that the engineers out there need a more complex solution than what we have out there with a single input single output power supplies are becoming more complex with multiple outputs and they needed an ability to trade off various architectures and whatnot. So my my role in it was to recognize that need. Came up with a concept that I drew in front of these tool designers. The, the people who actually do the [product] software.

A: Okay.

E: And I explained to them. This is what we need. And of course they were excited that we are we are solving a need out there. And hopefully, hopefully that will lead to more sales of our devices.

a: Uh huh.

E: And they asked me to draw more details of the concept so they can implement it, they recognize that these are software engineers don't necessarily understand the power supply design. They may understand some hardware aspects of the electronic design, but may not understand the details of what goes behind designing a whole power supply.

A: Right

E: And and a subtle thing here that I mentioned might come to mind is, there are different disciplines even within electrical engineering. And so people are designing power supply. Some people are designing sensors. Some people are designing, you know, maybe the antennas and by that sort of stuff.

So my role in this was to explain how we could come up with this [new product]. What we call a storyboard so. You know, create. Create different scenarios, through which an engineer might have to go through. You know what, what, what different aspects might they create, though. This was probably a you know, multiple page maybe 50 or hundred page document where scenario number one, they could come up with this if it was a 12 volt to two outputs, they would consider this if it was a 48 to five volt they will consider this. And and at some point in time we were we were going back and forth about what can they realistically implement.

A: Uh-huh

E: And this went on for I would say about two or three years. Yeah, we were we were coming up with the calculation, so on. And there's number of calculation involved here. In designing a power supply system. We were doing. Me and some of the people that work for me. We're creating these scenarios on spreadsheets and PowerPoints, and writing it into a Word document about this is how should, how you should design the software. And then at one point in time, there was a in a meeting. Bright mindset from the other group, not us. We really need to base this on something we already have.

A: Okay.

E: And so, there came the idea of linking the [older product] to the [new product]. So what we did is, and if you listen to that video that I sent to you, [Name] talks about layering the [new product] on top of [older product] and [older product] scenarios.

A: Okay.

E: And so we said anything any component from [company] and now [other company] that's going to be a part of this [product] is going to be based on something that's already there in [older product] and if it's not there. If it's not there. We have to implement that first. So the simple designer from a single input to single output based on a single component of [company] has to be there as part of this tool for it to be leveraged into the [product]. And the reason for that is, then you can leverage on top of all the calculations that are that are done at a fundamental level. Use the input output of that into higher level calculator and the higher level calculations become simple addition, subtraction, multiplication, rather than solving a more complicated engineering problem at a single input single output level.

A: Okay.

E: And and of course the rest of it is all the detailed implementation, but. But this is what went goes into a complex problem solving. First of all, it's recognition of the need. Second of all, having somebody that architects, the concept. Third of all, you know, a group of people that can actually implement it and at the end of it, of course, it's a it's a group discussion and trade offs back and forth between the actual implementation.

a: So It sounds like when you were like. For all the different possible scenarios that an engineer could put in for what they need and their power supply. You had to think through each individual one? Or was there. Was there some sort of generalizable solution that you came up to came up with for that? Like how did the How did all of the different possible combinations get get programmed in there?

E: So we limited it. Naturally. So one way of limiting it. Like I said, was to only limit to the components we have available from [company]. That limited the infinite possibilities.

A: Sure.

E: The second way of implementing limiting. It is the number of stages we allowed

A: Okay.

E: So as I said you could go from the 48 volts or hundred volts in a single stage, all the way down to one volt. Or whatever the smallest possible output. And everything in between. So you could have one stage two stage three stage in between. And we limited the number of stages, if I remember right, we limited it to two intermediate stages. So you could go from say 48 to 12 volts and from 12 volts to five volts but that's it. Then five volts…

A: Okay.

E: From there on everything that's subs. Sub 5 volts would have to be created from that 5V. And you could go from instead of 12 volts to 5 volts. You could go five volts and three volts or whatever you choose, but there would be only two more stages and not a third stage as 12 volts to 5 volts three volts to then the subsequent voltages.

A: Okay

E: So that so we made some conscious choices of how to limit this possible permutation. But what we didn't limit is the engineer's flexibility and choosing what those intermediate voltages are

a: Okay.

E: Or how many whether it's a one stage or to two stage, or zero stage. We gave all those options to the engineers.

A: Okay.

E: And as a matter of fact the tool starts out with saying describe to me your inputs and ultimate outputs. Don't tell me what the intermediate stages are just tell me.

A: Interesting

E: Tell me what you want from the input all the way to the outputs, tell me that you your power supply is coming, say from the AC wall plug, and you have 15 different outputs - one volt two volt three volt and so on. As we did this, we also recognized by the way that. Sometimes in the system. There may be three or four components that are all part at the same voltage level, say 3 volts. And we give the option for the engineer to say I want those three volts separately supplied or combined. So say you have two three volt powered components, one requires one amp and another requires two amps shall you have a three volts three AMP combined output or shall you have two outputs one that's thee volts 1 amp and another one that's 3 volts 2 amps. And we left those flexibility up in the hands of the engineers.

A: Okay.

E: And and those are the kinds of inputs that we have coming from the product line into the software implemented, saying, no, no. There are people who really want to split and you cannot combine them. We want that flexibility in the hands of the user.

A: Right. And so, is that something that from, from your experience in power supply design you knew that in some situations, you would have wanted one way and some of the other way, and so you knew that that you know that they would want to do that too?

E: Correct. Correct. And, and an example of that is what happens sometimes is that that second output is actually going off the motherboard. So if you think of your laptop. Sometimes you have these multiple USB ports, right, you have two USB ports. Well, each of them has a three volt output

A: right

E: And sometime One is plugged in, and sometimes the other is plugged in, and sometimes only one is plugged in.

A: Right

E: Well, we really would like those outputs to be separate, even though they are really the same three volts in one amp and you cannot combine them as three volts to 2 amps. And then another case, there may be one single component that's on the motherboard and another component is exactly alike and they could be combined together. So there are situation of both kinds. We knew that from our

Interaction with the customers. The software team Of course they were. They implemented their own their own. They don't talk to customers that often

A: Um, and so then, so now you had the the plan. For how to implement this, and then. And so then, was it then all the software engineers or were you still involved in in testing out what they were producing, or what happened there?

E: Ah, very good question. So in all my engineering experience all of this stuff that we just talked about, usually about 10 or 20% of the work.

A: Okay.

E: And so the natural question is, what was the remaining 89 another work. It's, it's called testing and validation. So what you have to do is once it's, once the framework is implemented, you have to come up with a lot of test scenarios. And try out different scenarios. So all that document that I talked about earlier. Came in handy.

A: Ok

E: We debated whether we should hire some interns to go do this testing or do it ourselves. And we said, you know, even if we hired interns or, you know, some students to go do this, we'll probably end up having to sit with them and walk through them. What's okay and what's not okay. We just bit the bullet and did it ourselves.

A: Okay.

E: Yeah, and me me and my team did a lot of testing work to prove out that this thing does does work as we would wish it to be. And as with everything, we did find some scenarios that broke the tool and went back and said, Well, this particular thing is not working. Why might that be and then there are things that we found that needed to be fixed and some things where we needed to make. Choices, and in the scenarios and then we made some compromises.

a: Okay. And so things like. Like the the things that you the decisions you made to kind of limit the scope of it. That was done not at the testing phase. But initially, but then you found some other things where you had to go back and make some choices?

E: That's right. That's right. So during the testing phase we found a few more compromises that we hadn't thought about earlier in the definition of the tool. And that does happen from time to time.

It was very few. There was very few cases. And as a matter of fact, the cases where we did come up with those limitation. We made some choices we went back in and plugged in the tool. About three or four years later, and the reason for those compromises was there were some, if you remember I said we made a conscious choice to only implement the scenarios that were based on what was available in the original [older product] underlying tool.

A: Right.

E: So there were certain component that had to be in the tool. To implement the scenarios for which we have to make the compromises at first. So four or five years later when we actually had those other components in the tool as well. Then we were able to plug back that gap that we have to make a compromise for

a: Oh, that's nice. Um, so is there is there any more of the process that you don't think you've described yet before I asked more questions?

E: Um, yeah. So, so the sad part of this whole thing is that this whole whole tool was based on a web technology called flash

a: Oh, no.

E: You know what I'm going to say next. Flash has been decommissioned and so [company] had to make [company], my employer, had to make a very hard choice last year whether to continue this tool in its, in its original essence or give some other choices. And unfortunately, we have to decommission it as it was ---- several years ago. So the capability exists, but not in the way that we implemented originally. The original implementation was very flexible, and it gave the customers the choices they wanted. And we're walking away from it. And and customers seem to understand why we're doing what we're doing.

A: Yeah

E: And we are more hands. Near the customers these days than we used to have it so there's not as much of a need for everything to be done just completely on the web. So there are people that are available. So essentially use the same kind of stuff. That we did before this tool existed and give it in the hands of the customers.

A: I see. That's, that's too bad.

E: Yeah, it's unfortunate, but yeah. More question for me. What else, what else do you want to ask? I think I've described the tool. The problem. And what we did, hopefully. Yeah.

A: Yeah, no. Certainly you did, um, so that that actually answers, most of the questions that I initially had but a couple. So what do you think were critical decisions that you made in the process of making this tool?

E: I mentioned some of them. One of them has to do with You know, what limitations or compromises. Do we want base ourselves on. Yeah, and I think that was a very leading good question that you asked is, you know, how did you limit the the potential choices and the decision that we made about basing it on [older product] existing design devices, the choices we made on, you know, limiting the number of stages. And those were some very important critical decisions. I would say also the division of responsibility worked very well. The people that worked with each other understood each other's expertise and respected it. I've been on other teams where there was a lot of Prima Donnas and it doesn't work.

A: Uh-huh

E: At the end of the day, it is a team effort and different people have different expertise that are bringing to the table.

A: Uh huh.

E: It's a, you know, none of the problems that none of the problems that are this level of complexity are a single person implementation.

a: Right. And were there any particular challenges that came up along the way other than this final issue of flash got decommissioned?

E: Yeah, as I mentioned, also we had to make some compromises when we did the testing.

And we had to stop. And go back in and implement a few more components into the, you know, building infrastructure before we could make those additional stories on the on the top of it.

A: Ok

E: Well, fortunately, none of the limitations had to do with people's expertise. I've been on other projects and other teams where that was a limiter. We just didn't know what to do. We knew that there was a requirement, but we didn't know how to go fulfill it. And there are still there are many in engineering. There are many unsolved problems. We end up with that, fortunately, this particular problem that I'm describing to you. Didn't have any of those. We had a fairly competent team on my side as well as the people who are implementing it.

a: Okay. So along those lines was there any new knowledge or new information that you had to collect along the way?

E: Some but very limited. So one thing that we had didn't mention this earlier. One thing we had at our disposal is ability to collect the data. On who is using [older product] and how they're using it.

A: Ah.

E: So early on, back in the early 2000s, I guess we had made the decision that the [product] tool was a [company] tool we didn't want to put it out in the industry. For our competitors to come pick it up. And one way of getting one way of limiting that was by by allowing only registered users to use it. So registered users meant that we had their Login ID, and by that token once they logged in, we know we knew who they were. So while there while hiding their identity by a user ID number, we were able to track at a aggregation level. We were able to track. How many designs of which different types are being done.

A: Ah

E: So we knew going into it. Remember, made some choices about how many different stages shall we limited to how many different inputs and outputs, might we want. So we had already information based on prior usage of what people were doing with the [older product] infrastructure tool. That helped us quite a lot in making some of the choices that we made.

a: Okay, great. Um, and so, something that's come up in a lot of fields is the, that people rely on models. And so I'm wondering if you could just talk a little bit about if you used models in this and what model means to you?

E: Yes, yes, good. Really good question. Um, so that will that will take me to the actual [product] infrastructure itself.

A: Okay

E: Um, So when one and this will get a little more technical than I had wished in this call, but to implement a power supply, you're going to use an electronic component that's called a DC to DC converter.

A: Okay

E: And that DC to DC converter basically takes in some sort of input voltage is some sort of an output voltage and it has some surrounding components like an inductor capacitor resistor, that sort of stuff.

A: Okay.

E: The DC to DC converter is a highly complex electronic device. We, there's no way to take every single component that's inside that complex device and and try to put that into a higher level calculator like [older product]. So we abstracted.

A: Okay

E: We abstracted to a few simple characteristics of that device. All of our electronic components whether is from [company] or other competitors have something called a data sheet.

A: Okay

E: On that data sheet there are pages that describe the electrical characteristics in a table format. And they talk about things like what's the minimum input voltage that the device can sustain. What's the maximum input voltage that it can sustain. What's the maximum current? What is the efficient, effective resistance of the device output and things of that nature so many characteristics of that nature. And we use those data sheets parameters. To come up with a table of critical characteristics that are necessary for this power supply design.

a: OK.

E: and now by doing so, we are effectively limiting this from expert users.

A: Okay

E: An expert user might go into the data sheet and look for more parameters then interpolate between, between the values that are specified there and come up with, Perhaps a little more efficient design or a little smaller design thing of that nature. We made some conscious choices to to make it. Easy to use. But by doing that, we are limiting its ability to perhaps a novice or a medium user. An expert user could come up on their own, with even more even even better design. But that expert would probably take longer time to do it. So we were going we're going for quick easy usage, rather than more complex perfect design.

a: Right. Makes sense.

E: I hope I addressed the question you're asking about the modeling. Right. So, so there was parameters we abstracted the products into right

a: And that's your model, then yeah.

E: Yeah. And that model does by modeling that way does limit. The complexity possible from output from the design from the, from the tool.

a: Right, right. That makes sense. Okay, great. Um, and so a final question then. Is thinking about Trainees or interns, and, or people with less experience that you've worked with. What difficulties in problem solving. Do you think they run into?

E: Good question. So. Take, take this context completely out of this. So suppose I had a new problem.

To come up with. Right. I mean, it was not a [new product] say it was a different problem that we're solving. What would. What would a summer intern or what would a new college graduate coming into the pool of engineers with us. What, what might they be faced with and what would they, what might they have not come up through their engineering education? I mean, I think you're you're headed right now.

A: Yes

E: So the thing that I consistently see, whether it's a summer intern or whether it's a new college graduate is the need for working in teams. I think other than this other than the senior design project.

At the engineering schools. I don't see that many collaborative projects that people work. Work on during their, at least in what I've seen in the engineering education, even in graduate school, there is a tendency to emphasize individuality.

A: Uh-huh

E: Right down to the PhD thesis and so on, that people say we. We emphasize individuality. And what did you particularly do. I mean, even in the question you're asking me, what was your role into the stuff

A: Right.

E: And in reality the problem solving is not a single person task.

A: Yeah

E: It is a it is a group task and and the recognition that you need to respect other people's expertise and be willing to contribute. What you uniquely can provide versus what somebody else can provide and and, and that listening to some other expertise and, and working collaboratively is not something I've seen emphasized in schools.

A: Right.

E: And maybe there are schools that do that, but I haven't come across too many of them.

a: No, I think you're absolutely right. So any anything other than working in teams or is that it?

E: So that's one aspect of it. And that's probably the major aspect of my, I would say criticism, if any.

The other thing is that different schools emphasize different disciplines right and and i and i this is not a criticism. This is a more reality. I mean, you have the teachers you have, they have the expertise they have. And the curriculum you offer is the curriculum you offer. So there are going to be limitations on what one university teaches versus another university teaches and, and when we hire students. We do look for that. If we are looking for a person in the technical marketing stuff or we are looking for somebody who is a power supply kind of person versus somebody who is. analog versus digital person. So we, we have seen some universities being better than others. And I think it just, just a fact of life.

a: Okay. Um, well, I think you've you've answered all my questions. And this was this was very helpful for me so thank you very much.

Earth Science Faculty

A: … what were the detailed decisions that you made; go through step by step how you, starting from how you picked the problem to how you figured out what you solved.

E: Well, I'll just use an example of um, a project that my grad students and I worked on over the last decade.

A: Ok

E: Which was trying to understand the earliest stages of the evolution of the Yellowstone plume and the production of Columbia river flood basalts. And um, the model here is that there's a plume that comes up, uh, the upper part of that plume melts, in the mantle, and produces these gigantic floods of basalt. The Columbia river basalt is one, but they are also all over the world, and now we're also increasingly thinking that they may cause some of the major extinction events

A: Ah

E: The particular ones I worked on, the Columbia river basalt, I actually called them the friendly flood basalts, because it's actually looking like if anything they actually bumped up the CO2 just enough to make things warmer and nicer in the middle Miocene, but not enough to kill off things.

A: Interesting

E: Yeah. So. Anyway. So the. And I have made my career working on mostly on explosive volcanism, things like Yellowstone and Long Valley and places where there are rhyolitic things that spread ash continent wide. So what we did, in terms of using. We were trying to use this as a model to, um, use where the rhyolites, that is places where the continental crust was melted by this plume material coming up, to outline the footprint of where this plume initially impinged on north America.

A: Uh-huh

E: And we had some ideas from the dating that was out there of rocks that were existing..

A: Ok

E: But these were areas that nobody had mapped very much, in eastern Oregon, south eastern Oregon, northern Nevada, pretty wild and wooly places

A: Uh-huh

E: That aren't really accessible. Um, so there were some dates out there. So we undertook a mapping project, a geochronology project, and then also analyzing the rocks to sort of get at where the melting happened in the earth where those magmas came from. And so that was the model. The initial thing that we did was just reconnaissance. Got the literature together. Found the places where there were relatively recent dates. Tried to put together the story and places where we thought we should go look

A: ok

E: And so we went out, and one of my grad students, who now runs the ion-microprobe. This would have been over 10 years ago.

A: (laughs)

E: We went out to north, north-western Nevada, where there was some existing dates, and there was some information, and did some prospecting around there

A: Ok

E: You know, just driving around, looking at things. And I thought that we could. We found evidence for these collapsed calderas that are things that are maybe, say 15 kilometers diameter, where explosive eruptions happen and you erupt so much magma that the roof of the magma chamber falls in

A: Ok

E: So sort of like Crater Lake, but on a much bigger scale

A: Ok

E: Like the biggest one at Yellowstone that happened 600,000 years ago spread ash all the way to Texas

A: Wow

E: Covered the whole United States. Much bigger caldera. So the ones we found are smaller, maybe a third the size of the ones at Yellowstone. But there was evidence for them. Some sketchy geologic evidence in the literature. When we went out and looked, I've worked on these things enough that I saw some clues, that I thought "yeah, I think there's other calderas out here too."

A: So what are the clues that you were?

E: So for example, one of the features are caldera lake sediments. So when you have these lakes, you get a particular kind of sedimentation because they're holes in the ground, but they're not integrated into the drainages. So rather than have regular river gravels and things coming into them, the only deposits you get are very very fine grain dust that falls out of the air, ash that falls out of the air. Or diatoms, which are these little silica things that

A: Yeah

E: That grow in the water and they grow and then fall down. So you get things that are diatomaceous things like these (hands fossil fish in diatomite)

A: Yep, yep!

E: So very light, right (both laugh) And um, so if you find those, that's an example of a lake. So there are other ways that you'd map lakes. There are other ones [in Nevada]. That they're not all caldera lakes, they can be in basins too

A: Uh-huh

E: But it's kind of suspicious when you've got a ring of rhyolite lava domes around an area where you've got . .. You know these sediments. Mm.

A: Interesting

E: that's a little bit suspicious. Or alignments of lava domes. Instead of being random, there's' a few of them that look like they're from the same age, and they sort of form an arc-like pattern that look like they're erupting around the edges of one of these features. Or hot springs, or hot spring, ancient hot-spring deposits that are erupting along these, what could have been these features.

A: Ok

E: So those are all pieces of evidence that you can either find for yourself in the field, or you can get from old maps. So in many cases, these are areas that had been mapped in the past, and the thing about a geologic map is if it's done well, even if the interpretation is wrong

A: Ahh

E: Right, because they didn't have a context. Like you know, as people, for example, the plate tectonics revolution went through. That didn't make the old maps wrong. It was just that you had to go back and reinterpret what those units meant.

A: Uh-huh

E: So the same thing happened in this situation. A lot of the mapping in the western US was done before people really had an understanding of formation of calderas, the pyroclastic flows that are formed on eruption of them.

A: Uh-huh

E: And so, But if you go out with the right glasses on, reading those maps, reading the literature, you can often go "oh" and you can go right to the right place and check it out.

A: Uh-huh

E: So that's what we did. … Um.

A: And so you picked to go to the places you went in Northern Nevada because …

E: There was preexisting

A: you saw there was evidence on the map

E: Yeah

A: that said there were these calderas

E: Yeah. There was pre-existing, right. And then of course the other thing that is fabulous now, you know that we did, sort of. Once we got into this. So that was the first thing we did. [Name], the student who did most of the work on this, went out and spent months mapping, doing traditional mapping. Collecting

rocks. Then we did the geochronology. Then you can show the eruptive history, that yes, these lava flows came up along the fractures along which the calderas ---- (uninteligible), blah blah blah. So you know we did the geochronology, we can also use the chemistry of rocks to sort of correlate units. So if you collect something out here, and out here, that had been disrupted by Basin and Range faulting, so that they're no longer looking like the same unit,

A: Uh-huh

E: but you can date them or you can get the chemistry on them and show that they're the same age, that it's the same.

A: Uh-huh

E: So we used geochemical fingerprints, and dating, to correlate things around as well.

A: Ok

E: So. Once we did that, then. You know, he produced quite a detailed map in doing that. Of a couple of calderas and then a larger scale map. Um, we got pretty good at knowing what to look for.

A: Ok

E: So the next student that went out, found, again found several calderas. This along the Nevada-Oregon border. And um, we then. And we were finding older and older units. We were trying to identify what are the oldest units associated with this Yellowstone plume?

A: Uh-huh

E: That's sort of motivating some of this.

A: Ok

E: And the second area we went in we found things that were even older than the first. But we had a few orphan units there that looked from the stratigraphy that they were even older.

A: Huh

E: And they, so we started looking around. There had to be another, other calderas that people had not identified.

A: Ah

E: And by now, um, I could make some guesses where they might be. And now you can get on Google Earth, right, and you can see features

A: Uh-huh

E: That. This would literally not have been possible 15 years ago, right

A: Yeah

E: And basically I found some features that I went "I think there are some calderas there that nobody has identified." And we went out there, and, there were.

A: (laughs)

E: And so [another] student who identified, who mapped, a smaller area of one of these calderas. So now he has identified what is the oldest um, silicic, rhyolitic eruption associated with the arrival of the Yellowstone plume

A: Wow

E: And of course since the plume comes up, hits, and um then of course North America has moved over it, so now the plume is under Yellowstone. And so, um. That was a, that was sort of the motivation of it. And there were some interesting things that. So that was very much a basic science

A: Uh-huh

E: Sort of thing. And then another thing that came out of it was the realization that again, a basic science thing, but something that has implications for other problems, is, um. These flood basalts are extremely difficult to get ages on.

A: Ah

E: Because they have very low potassium concentration, so you can't do potassium-argon, well you can do potassium-argon dates, but they're terrible

A: Ok

E: And so, basically, and the rocks are altered. And so they're very very hard to date. So one of the problems we had was we didn't know how fast do these things erupt? Do they come out over, um, a million years, 10 million years, or 10 thousand years. And all the dating had been showing over time, over the last 30 years, it looks like the period that these flood basalts come up gets shorter and shorter. As the quality of the data got better and better

A: Interesting

E: That it was getting shorter and shorter. And the reason this matters is if you're going to blame the end-Permian extinction on a bunch of flood basalts that erupted in Siberia 252 million years ago, you can't let them come out over 10 million years, right

A: Right

E: Because the end Permian extinction was an event that, we didn't know exactly how fast, but it was pretty fast.

A: Right, not 10 million years.

E: It was not 10 million years. You have 95% of the species are gone. So this was. So something that, if things erupted over 10 million years. First that might not be a bad enough effect globally in terms of

Sulphur and CO2 getting in the atmosphere. And so you need to take all those basalts and everything they carry that's bad

A: Right

E: Whether it's mercury or CO2 or Sulphur or whatever, if it's going to have an extinction event. So there were. These were very hard to date.

A: Uh-huh

E: But because there were these rhyolites erupting in the continental crust. The rhyolites have in them minerals that are easier to date. Whether they're feldspars or zircons, you can get highly precise ages.

A: Ah

E: So what we were able to do in the Columbia river basalts, some of these eruptions were going off simultaneously as the basalts were flowing in, and so they're interbedded.

A: Oh interesting

E: So by dating the ash layers and correlating them to the ignimbrites, we could get highly precise ages. So in other words we could say that these things were 16.408+/- .008 million years.

A: Wow

E: Ok, So we're actually talking about really short timespans that we can date these. Whereas previously for example Columbia river basalts everybody said "well, they probably erupted within 1.5 million years." What we could show was that at least the section we had erupted over at most a few hundred thousand years.

A: Wow

E: And we, and that also allowed us to calculate volumetric eruptive rates.

A: Uh-huh

E: Ok, which also tells you something about the flux of CO2 and Sulphur. And since they, you know, in terms of the Columbia river basalts we knew didn't have a big effect on climate. But so what that was telling us was, so it wasn't quite the same as doing this in Siberia where we think we have the ones to blame. But the point is it was the first time that actually somebody was able to do volumetric eruptive rates on basalts, so we can say "well if it's this level, it's not enough."

A: Right

E: Right (both laugh), it's got. Because if anything it looks like it might actually correlate with a bump in the, what they call the mid-Miocene climactic optimum. Where things were actually a little bit --. So that was happening at a time when people were dating ashes using zircons.

A: Uh-huh

E: So basically now it's part of the conversation that we now realize that flood basalts erupt over a really short period of time. So they are definitely capable of having global impacts in terms of acidification of oceans, raising CO2. the main effect looks like it's short term might be sulphur getting in acid, acidifying things. But long term is you put all that CO2 in the atmosphere, and you raise temperatures by 10 degrees C, and basically all the plants and animals can't adapt that quickly.

A: Right

E: Right. And the other thing in the oceans is that basically, the, when you raise temperature you raise metabolic rates. And then that drops oxygen levels down

A: Uh-huh

E: And then you basically kill everybody off

A: cause there's no oxygen

E: (laughs) There's no oxygen. And so, we're starting to get to this. So that was one thing that came out of. It was not. I guess the reason I'm telling you this story is that I think this is a not uncommon thing that happens with field-based studies in geology, that may be aimed at answering one particular question, but then if you're kind of smart and looking at topical things it might be interesting

A: Uh-huh

E: You can, I realize that gosh, some of these units, I think I've got correlative ashes that are interbedded with the Columbia River basalts. And once we did that, then a lot of people went out and started looking for them

A: Right

E: And then they found them. And so then, you know, that story is becoming, you know even more, better defined. And then on a practical side. Um, one of my grad students [Name] who had been working on a place that um, they knew there was lithium around. In, um, the McDermitt caldera, and basically he found other sediments where there could be lithium, and based on his understanding of the other calderas that were associated with it, um, came up with a generalized model for how lithium deposits could be formed in, um, caldera lake sediments

A: Huh

E: And, this got a lot of press. If you, kind of embarrassing sometimes. Because it would go titles like "super-volcanoes will, you know, power… electric vehicles"

A: (both laugh)

E: So if you look up that, super volcanoes and electric vehicles. You'll see that it got, you know, widely picked up, partly because of the cleverness of our school's PR group. You know I went to them and I said I think this might be a really good example of where some basic science that you know was not aimed at anything practical has turned out has been really kind of important. [mention student's next job]

A: Calderas.

E: Yeah, calderas and lithium deposits. And so they thought, because they're always trying to do that, trying to find ways that basic science turns out that it isn't just navel gazing

A: Right

E: (laughs) That it's actually something worthwhile. And um, so that was actually, you know that was pretty satisfying to me. To do something

A: Yeah

E: And the other aspect of this was that, thinking about sort of pedagogy or the way we think or learn or what we do, was that [Name] and I after having these experiences of basically finding new calderas in three different places. Got pretty good at figuring out what are these clues. And then he basically went out and spent a week and found, probably found another whole set of them, in Northern Oregon

A: Ah

E: And so, um. Yeah. So I guess, what am I trying to. The point I'm trying to make about that is that you're developing generalizable things. From the specific

A: Right

E: Right, to you see enough of the specific that you start to come up with a generalized model.

A: Uh-huh

E: That's what they do with ore deposits, right?

A: Right

E: Each one is weird in its own way. Because that's what ore deposits are. They're weird. They're special. Otherwise they wouldn't be rare. But you see enough of them, and after a while you start to pick up like, oh, these are the features that they have in common, and you come up with a model for, um, ore deposits. So the same thing can be done in many geological

A: Uh-huh

E: Field-based geological things.

A: And so thinking about this project, what were critical decisions that you made, um, that let you be successful?

E:… I'm not. I'm trying to think of what critical decisions would be. I think the, you know the. The um, the idea of going out to, you know, looking at these ashes. Where that turned out to be one of the more impactful things we did.

A: Yeah

E: Because in truth you know, only a few people care about calderas themselves. Is, is being willing to take a little bit of risk that this, whether this is going to play out or not. right

A: Ok

E: And um, going and collecting the ashes which was kind of a nuisance, because they were not easy to get to. And um, separating out. I guess what I'm saying is that it was a little bit of a long shot. I was not sure that it was going to work

A: Uh-huh

E: And then developing. Being willing to devote the. Giving props to my grad student for being willing to devote enough time to get enough geochronological data that you kind of beat up the problem with statistics

A: Uh-huh

E: In other words, you don't just go in and grab one or two dates, or you know, and then try to write a little quickie paper, which we could have. Instead he went in and he got lots of dates, we put them in stratigraphic order, because then people believe you, right, if they come out in the right order, then oh

A: Uh-huh

E: Maybe these are right. (laughs) and then re-dating the same thing over and over so you have some estimate of errors. So then you can actually do calculations of okay, this is the time gap of these two plus or minus x and you can actually do calculations that have errors on them

A: Uh-huh

E: That allow you to be quantitative about things. So I think that was. You know, first recognizing that there, that I had access to a geological … type of evidence in these ashes that, that maybe I uniquely among, cause otherwise, people should have seen these before

A: Right

E: It's right near a road. It's in a cliff like this

A: Really? (both laugh)

E: So if it wasn't for the young legs of my graduate students, it wouldn't have happened. But they were obvious. So it's not like there was any, you know, we weren't hacking through the jungle finding these. It was more just putting together the. Wait a minute, those are ashes up there. We know about these other things. We can date these.

A: Right

E: We can really contribute to this important discussion

A: Right

E: And then being willing to have the patience to be willing to do what it took to produce a dataset that other people would find convincing.

A: Um, and so you talked about the, the amount of data that you needed in order to have some statistical power

E: Yeah

A: Were there other, what all went into that dataset in order to be convincing?

E: Well, I think it was just basically time

A: Ok (laughs)

E: Time and frustration. Because anytime you do anything with a mass spectrometer, things go wrong. Anything that it's instrumentation, where you're data heavy on the instrumentation. It's gonna take time and there are going to be intervals when the machine doesn't work, or whatever. So there's a persistence factor that goes into that.

A: Ok (laughs). And so at. … what

E: And I think the, the other thing that, um. … I think the other thing that I have, that I don't see in every one of my graduate students, and that some of them have and have had the best. And I'm not sure that I always communicated very well. Is that I love data. I love like, sitting around, and you know, looking at plots of geochemistry, or you know, trying to correlate ashes, or something

A: Ah

E: I just find it fascinating. I like to sit around and look at maps. I like to look at geochronological data. Data speaks to me. And I, what I, what I'm often surprised about is grad students who will collect data and then do nothing with it.

A: Mmm

E: It's like. I… and I obviously have failed.

A: (both laugh)

E: Because I haven't, somehow I haven't' transmitted this sense of beauty, you know, of letting the data speak to you.

A: Uh-huh

E: And tell you the story, and sometimes, the data point that doesn't look right is the thing that is the key.

A: Uh-huh

E: Right. To, I mean, either sometimes it's misplotted. But sometimes it doesn't fit and there's a reason in that if you figure out that reason, it's important. This of course will bring my old-fart rant here. And I think part of the problem is because it's so easy now with plotting programs

A: Ah

E: People. You can generate any plot that you want. You go in and you can make any X-Y plot or 3D plot or anything you want, without any thought at all. And so you produce these things and they all look beautiful. In the old days, you know, when I was in graduate school, you basically couldn't do that. You were mostly sitting there with graph paper.

A: Wow

E: So the thing you did when you did that was that if, as you were, you were actually developing, cognitively you were developing an idea of what the data meant as you were plotting it

A: Uh-huh

E: And then when something would be out there, you would go, well that looks weird.

A: Uh-huh

E: So the first thing you would do was go back and make sure you had plotted it right, there wasn't some glitch. So that's again my rant. That a lot of students will have these plots, and there will be a few out there and they won't bother to figure out, well why is that?

A: Yeah

E: So I think looking at data is, uh, is something that, and letting, and trying to come up with a narrative that explains it all. I mean, the thing I, I try to inculcate in my students in terms of working in research is the idea that when you're writing a paper or, it's a story.

A: Mmhmm

E: Right. And you're telling a story and you're trying to communicate a story. So how you bring in the data is part of that narrative.

A: Right. Right, so can you talk a little bit, trying to bring it to the specifics

E: Yeah

A: of the project talked about, about when you were looking at that data, how you went about looking at it – what you did to look at the data?

E: Um, well, I think just looking at lots of different plots, for example. We're trying to, so for example for correlating things. We'd look at lots of different bivariate plots of different elements until we arrived at a set of elements that we thought were most distinctive. In other words, there was enough of a. They varied enough among units that they could give you some dispersion.

A: Uh-huh

E: But they were also accurate enough and precise enough in the measurements that you could count on them. And it also, in doing that, it also brought to bear some information that I, you know, that we know based on what happens when rocks are weathered. Certain elements like the alkalis are easily disturbed, and so you don't want to base anything on the alkalis

A: Right

E: Or. So there are certain elements that you know don't work just sort of on a first principles chemistry background.

A: Ok

E: And, um, so, you know sitting down and looking at those plots. So that's a pretty simple thing. In other words, basically then you get a geochemical fingerprint of some kind of ashes. So you just do a matching basically that way. You could do it statistically, you know, with cladistics and things like that, but I think actually, the problem with that. I have students that do that especially in [course] because that's kind of what they're taught to do. The problem with that is that sometimes you want to actually, for example if you're looking at data, you might find things will plot together on one plot and then on another plot they don't plot together.

A: Uh-huh

E: But there might be a reason for it. So for example, I know that in ashes, every now and then rubidium numbers are just off the charts. It has something to do with basically kind of like a water softener effect of ion exchange in glass

A: Huh

E: And so, you shouldn't worry about that. Right. So in other words don't throw out that particular baby because rubidium looks wrong, you just know that that can happen.

A: Ok

E: And so, but of course that means that that's an expertise. And talking about what experts know and what students don't know. Is that only can be, it's hard to, um. That's hard to transmit to beginning researchers. Right. Um. That's just, knowledge that you've picked up over time. And I'm not even sure that you would ever, you wouldn't find that written in any book

A: Ah (laughs)

E: And so there are things like that. In terms of you know, trying to think about how those, what. How I would actually, you know, you could teach that in a beginning class. You know, first by taking all those ringers. You know the ones that are a little bit hard. You could, for example, give students a bunch of chemistry to correlate things, or for example do it on obsidian sources.

A: Uh-huh

E: You could do this in an archaeology class. Of saying, I've got, all this is a place where I've collected all these obsidians over the Western US, and this is their data, and here's some obsidians that we've gotten from archaeological sites. Figure out where they come from.

A: Uh-huh

E: Right. And then you could walk them through various, you know, letting them try various bivariate plots, or triangular plots, or various statistical approaches, like to figure it out

A: Uh-huh

E: So you could teach that sort of thing. If you wanted to. Yeah.

A: Um, … so going back again to the, to the caldera project, um. How did you decide when you… had an adequate, convincing argument to go publish or present.

E: Well, I think this is where geology is a little different from other things, right

A: Ok

E: Because the, you know the caldera story itself is a geologic history story. So that is basically you just publish it when you think your maps are good enough that you can do it.

A: Ok…

E: There's also the recognition that every map is a work in progress. Unless you're. Especially if you're a graduate student. You can only spend so much time.

A: Right

E: So, um. But I think, you know, even beyond that, except for a very few examples, like say people like [name], works at the U.S. Geological Survey and he can spend 15 years on a map, and probably it is not a work in progress when he's done with it; it is done.

A: (laugh)

E: Nobody else needs to go in because he's so like … But most things you do in academia you just don't have the time. It would be very unusual for you to do something at that scale. So certainly once you go on and work in industry, and even in most government things you would never be able to spend the time. You wouldn't have the luxury of doing that. So deciding when something is. Partly it's kind of the other way around. It's like "time up!"

A: Oh, Ok

E: "now what do we have that's publishable?"

A: Ok

E: Rather than, so for many things that are field based. And so you, so for example, most recently with my masters student, um, you know the map is not great. Because he basically just did it over two

summers. And we both recognize that, you know if this were a PhD and he had another year or two of field work and geochronology, it would be much better.

A: Right

E: So the question is what do you feel comfortable publishing.

A: Uh-huh

E: And basically, I think what you do is, you know, for example, in this case, if this ever gets published it'll probably be in a, you know I'm not going to try to put it in a high-rank journal.

A: Ok

E: Right. I might try to publish it as a map through a state geologic survey, or something like that. Um. So, you know, because I wouldn't want to have. Or I would try to publish it in a slightly higher, not a super high rank journal, because basically maps are almost never in Science or Nature.

A: Right.

E: Just the nature; they're short. Or even EPSL –Earth and Planetary Science Letters – the sort of main line journals, because it just doesn't have the space to put a map and all the descriptive material. But even, say, Geological Society of America, you know, I probably wouldn't try to put it there, or if I did I'd try to make it short and sweet and not make overly large claims for it

A: Uh-huh

E: So I guess that's what I would say is that for a lot of things that are map based it's more like, you do the best you can with the time you have and then you decide what is worth publishing and where.

A: Uh-huh

E: The project for example that we did on the, uh, the dating of the ashes. That was more, um. Again there was a little bit of a "time's up" thing in terms of you could continue to date ashes and look for more of them,

A: Mm

E: but in this case basically when we got a sequence of ashes that were in stratigraphic order and the numbers made sense

A: Uh-huh

E: And we could make some calculations, we figured that was, that was enough.

A: Ok

E: And we also recognized that it had time value. You know, in other words, people were kind of starting to think about the same things. So it was important to get it out.

A: Right

E: Um, even though you know, it could have been a little bit better with a few more things. But I think, I think people accepted the argument the way we did it. Um… again, we, in association with this lithium deposit thing,

A: Mhmm

E: We did some studies of lithium concentrations in melt inclusions, which are these little. Volcanic. When the magmas are sitting around there, crystals grow and they trap little bits of melt, and then when those things erupt on the surface, um, those little things do not outgas.

A: Ah

E: They're essentially like little pressure vessels

A: Ah neat

E: And so you can go in and make a slice through them and then analyze them with some kind of ion microprobe. And so we got, we did, we got some analyses of um, things from Yellowstone and a variety of tectonic settings. Um, and just analyzed the lithium concentrations to try and see well, what was it that caused lithium? In other words, did you have to have really high lithium concentrations? Was that required? Or were there certain kinds of rocks that were melted? And in that case, we only had about 7 or 8 different localities. Um, basically places I'd worked over my career

A: (laughs)

E: You know, where I'd gotten samples from. But the idea there was, this is kind of a crude way of saying it, but if [name] were here he'd remember our old instructor [name] used to say something about science, he'd say, he'd send his graduate students off to do something he wasn't sure was going to work and he'd say "suck it and see."

A: (both laugh)

E: You know, just, just try something and see how it works. Okay, so that was what this was basically that kind of science. Right. We were going to see, could we find anything systematic?

A: Yeah

E: And we did. We found, for example, that various tectonic settings had different lithium endowments, which wouldn't surprise anybody in ore deposits, but nobody had made these kinds of measurements for lithium before, so it was kind of a new measurement

A: Yeah

E: And then we were also able to show that you didn't actually need extraordinary lithium concentrations, because the place that we knew, McDermitt, that had them, had high, but not super-duper high values. You just had to have enough rock that you could integrate it over.

A: Ah

E: And that paper we, again, published in [high-tier journal], with you know that was. It was timely, it was data that, that weren't very many kinds of measurements. So there's certain things that you can do in, if there aren't very many measurements out there and you're addressing an important question, that you know that you can go to publication, um, with. If you were doing something in a more developed, something with a lot more mature field, you'd get shot down. Right, you wouldn't be able to get it past reviewers

A: Right

E: But if you're doing something with, where people recognize, you know that "well, this is an interesting data set". And you know, they look like they've done the best they can with trying to correct with blah blah blah blah. You tend, you're going to be okay

A: Uh-huh

E: As long as you don't make overly wild claims for it. Um, so that was the case where we, you know, I knew that it was not a comprehensive study, but it was topical, it was timely

A: Mhmm

E: Important sort of for larger scale issues, social issues, like where should we be looking for lithium?

A: Right (laughs)

E: And, um. So this. … So that was kind of another way to think about, you know, when is something ready to be published?

A: Right

E: So that was a case where it wasn't even a time up. It. That was the case, because he was still around. That was like, this needs to get out now before you get scooped. And also so that you can be on the leading edge of this topic, for my grad student.

A: Ah. … Um, so … As you were working on this project, what new knowledge or skills did you acquire?

E: Well, for example, I had to teach myself about zeolites. Which are minerals that form at very low temperature when ash interacts with water of various temperatures and alkalinity. I didn't know anything about that

A: Ok

E: So some of the interpretations of some of the caldera sediments, that because these were 15 million years old, the rocks have been altered.

A: Uh-huh

E: And so I had. I didn't know anything about that. So I had to learn about that because, well, because my graduate student wasn't going to. That was one set of data. Another set of data is, um, I had to teach myself about the magnetic timescale.

A: Hm

E: Because the dating that we were doing on these ashes also had implications for the ages of a very important reversal in the magnetic timescale

A: Oh

E: That happens, and had not been actually very well dated.

A: Oh

E: And we actually provided a better date for it. So I had to teach myself about that. Which I, I only knew kind of Geology 1 level. So I had to dive in and learn more about that. Um. What else? I mean, obviously I did learn a little bit about lithium geochemistry more than I knew. But that's kind of an extension of what I already knew. Um, I had to teach myself more about, and modernize my knowledge of, um, geochronology in terms of argon geochronology. Because the, although I'd done argon geochronology as part of my thesis and during my early years here at [University], I wasn't up to date on the newest stuff that's being done in the lab now.

A: Ok

E: So I had to, kind of, get myself up to date on that. So that I was, um, could better interpret the geochronology.

A: So since it's 11, I don't want to keep you too long. Um, but I'd like to also hear what your thoughts are on, um, in the people you've trained, what difficulties in problem solving have you noticed that they have, compared to your expert?

E: Well, one is this issue of letting the data speak to you

A: Mhmm

E: Of looking at data in different ways and really coming to grips with the data. It's just something that I don't know. I don't know how to. I've largely failed. I don't know. I can like force them to do it a little bit more, but it's harder to get them. Only the very… best of my students. Or let's put it this way. I've had a few students that did it intrinsically.

A: Ok

E: And then some that didn't but you could help along the way and would be able to do it, to get to the point where I knew that they were starting to do it because they'd come to me with some data problem. Like this student I was talking about, [Name], was terrible about it at the beginning. He used to bring me data plots that were just crazy. Like, that can't be right. You know that can't be right.

A: (laughs)

E: And he'd go back and "oh, yeah, yeah, the scale's wrong." You know, something that he should have picked up. And by the time he graduated, he was able to "you know, I discovered X and that seems weird, so I went back and blah blah" so he was able to do that. But that was. I don't. I'm not even sure how I train that, other than just doing it. Doing it myself with them.

A: Ah

E: Sitting there. And I think probably the reason [Name] got it was we used to have these marathon. He was just really easy to get along with, so we would have marathon sessions just going through his data, where we'd spend literally 3, 4 hours you know talking about stuff.

A: Uh-huh

E: So maybe that's how it got transmitted. I would have no idea how to do that in a class or anything

A: Yeah

E: Um. So that was one of the ones. Another problem that I have, I've had with students, has more to do with reading and writing, in terms of training

A: Mm

E: Which is. I guess. We all do this, but some people are faster at picking it up than others. Is the idea that when you write a paper or a research report, your goal is to tell a story. It gets back to this idea of a narrative. Your goal is not to give a blow by blow account of how you arrived at your conclusion

A: Uh-huh

E: Right, the reader doesn't give a --- about all the ways you got there. What you really need to do when you're making a scientific argument. And, I think this is again maybe something that needs to be taught. Um, or to a more general audience. Or maybe it's because they, or maybe it's a failing. Now that we're talking about it, I'm thinking maybe this is part of our problem why we don't communicate things very well

A: (laughs)

E: But they don't. in other words, there's the whole sausage-making that's science. Usually you end up with your conclusions, and you don't make a narrative of first I did this, then I did this, then I did that. That's not how you write a scientific paper. You write your conclusions, and as I put it, you often write a paper and then you defend each one of the things you say

A: Uh-huh

E: Right, you say "I know this because"

A: Right

E: Right, so you slam the door on all the people who are going "but!" "but!" "Uh" and you stop them before they get very far on that.

A: Ah

E: Right. You sort of anticipate what it is that might be objections to it, and you just deal with them. And that's. that's what you do, is. You don't give a blow-by-blow account of how you arrived at your conclusions.

A: Right

E: Um, and so, I kind of view often writing a paper as just slamming doors behind me of all the things that it could have been but it wasn't, and that I checked for. And so, getting students to actually be able to do that.

A: Uh-huh

E: Is hard. And some fundamentally just never get there. Um. I'm not sure, you know, in terms of teach. Like how you would ever teach that in teaching. Um, I think that's a. you probably could. It would be an incredibly time consuming thing to teach, because basically that's writing, which is really time consuming

A: Right

E: I uh, I have tried that a little bit. I, a couple of times I taught this [course] I was talking about. And it was sort of both an introduction to geology, but through a very particular lens of getting people ready to go to [place] and see everything that they were going to see. And then they each had to produce a field guidebook article, which is something that we do write as geologists.

A: Uh-huh

E: And you could teach them certain things, like. I mean a lot of them really improved their writing skills. And. But not only improved their writing skills but improved them in a very particular way, which is instead of saying "scientists think that…"

A: Uh-huh

E: Right, and then writing, is the. Is you'd say. "we believe that .. blah blah blah, because"

A: Uh-huh

E: "blah blah blah blah" Right, so that's what I'm trying to get them over that hurdle. And so, you know I think that that can be taught

A: Mhmm

E: Because I've seen that in these classes, but it's time consuming. Because you have to be willing to read multiple drafts and work with kids that, you know..

A: Time consuming on your front and on the class

E: Yeah. And so it's. so I think it can be done, and maybe there would be ways to scale that, you know make that at a scale that would be more. So. That was one of the difficulties training students. Another

difficulty was getting them to read the literature, which I'm sure everybody you've talked about complains about. But in their defense, there's so much more literature

A: Yeah

E: You know, I was thinking about this when I was grousing at one of my later graduate students. And then realized that, you know what, I used to be able to go into the [Place] library. Every Monday morning the library would put out all of the new journals

A: Ah

E: And so it was practice of all of the graduate students. You'd just sit down and leaf through all of the new journals. In all fields.

A: (laughs)

E: Because you could do it, because it was so little!

A: (laughs) right

E: So I'd do it for the petroleum geology (grumbles) and mostly I wasn't interested, but okay, done. But the point is that was actually something that you could actually do. And there's no way that you could do that now. So it's much more challenging. And then the other thing is. Is, um, how do you teach students what's worth reading?

A: Mmm

E: Because you get on the web and you just. Pfffff.

A: Right

E: And like, how do you know. and even if you go to google scholar, you get this whpfff. How do you know which are the things that are worth reading? That's a really tough one. So, for example, I often. When I teach my [topic] class, I have readings in a text book, and then I have tiny print on the syllabus, if you really give a damn about this particular topic, here's the other places to go.

A: Uh-huh

E: And what I often find myself sending students to are older literature.

A: Uh-huh

E: And the reason is that the older literature is actually more accessible because it isn't so full of jargon, right?

A: Oh, interesting

E: So that you can access. And a little bit more descriptive, the writing isn't as dense. So if you want to for example learn about calderas, going back and reading some of the papers that were written in, you know, the classic paper in 1968.

A: Mm

E: Is actually a really good thing to do. And you know, then you can sort of move your way up.

A: Interesting

E: Um, so that sort of, I don't think we have a very good way of teaching people how to do that. Um. And so, the other thing I often. You know I remember that I used to do, that again because of the online thing, is students attitude is if its' not online it's not worth reading

A: (laughs)

E: Which of course is really wrong, because a lot of the really classic stuff is too old to be online

A: Right

E: Is. What I used to call a proximity search. But it was a proximity search in that I would find one reference that I really liked, and then you'd go sit in the library in the book section.

A: Interesting (both laugh)

E: Right, that's the proximity. Like it's I'm sitting there. It's. and so you can actually. So I would say that's, that's actually not a bad way to start. To start in on a topic that you don't know anything about. So for example, this zeolite problem. you go and you find the call number for some fairly recent book on zeolites. Doesn't even have to be the book you end up on. You go in and you sit in the library and you just start pulling things out

A: Wow

E: So if you're lucky, there will be some recent really fabulous textbook or monograph that somebody's written

A: Right

E: And then it's like "woohoo your problem is solved".

A: Right.

E: So I think that's. anyway, that's one of the things that I think I struggle with. Is reading the literature, and then even the ones that do read the literature, kind of helping them know what's worth reading

A: Right

E: Um, I think. At least I don't know, maybe just in the last. Probably I don't know. Partly I think that it's hard for me to say whether my experience is real

A: Uh-huh

E: Because all fields go through fashions.

A: Sure

[student-specific discussion redacted]

E: And now probably the best students are probably going into some environmental thing or paleo-biology. You know, or whatever. And that's. so.

A: Interesting.

So I don't know how much of, you know, when I complain about millennials and the fact that they don't read, maybe it's just the cohort that I'm in particular dealing with.

A: Uh-huh

E: But, um. So yeah. So it's reading. Interpreting data.

A: Uh-huh

E: Um, is a tough one. That is hard to train students to do. And, um, what do I want to say? Um. Immersion. That's another thing that I find a little bit harder, compared to when I went to graduate school. Which is, I think graduate students now expect to have a life!

A: Ah

E: And, um. And because of that, there's a lot of graduate students that are kind of 9 to 5-ers. And um, and I understand it and I get it, and I. but there comes a time when you're trying to finish a thesis where if you're not working 60 hour weeks, you're not getting the benefit of, um, I don't know. I think there's like things that start happening in your brain when you're writing, and you're just concentrating on your writing.

A: Uh-huh

E: Things get faster. The connections between the little gray cells go faster. And you can actually, you know. and you're. You don't have to keep reinventing the wheel. You don't have to go "oh, you know, I thought I remember I got some data on that somewhere." Right?

A: Right

E: And you have to go off and find it. That's what happen when you drop a project and keep going back to it.

A: Ah

So it's this idea of your work pattern in research. That you don't always have to work like a crazy person

A: Right

E: But there are intervals in which great intensity are required if you're going to actually produce something that is, um. More than just kind of mediocre.

A: Huh. …. That makes sense (laughs).

E: But I think that's probably true of a lot of things, right.

A: Yeah

E: That's probably not just science. It would be, you know, if you're working in any kind of job. There would be times when

A: Right. When you need to really focus. Alright, well, thank you very much. This is great, very helpful.

Chemistry faculty (1)

A: What I'd like you to do today for me is to try to get an idea about how you go about solving problems in your chemistry work. So try to think about a problem you've solved or a project you've worked on, and walk me through the steps of what you did. So not like what you presented in a paper, but what actually happened step by step. And particularly think about decisions you made and what those were.

C: Okay. (inaudible). Solving a problem. One example that comes to mind right away, and I'm trying to think about if it's a good example or not.

A: Well, you can start, and if it's not, I'll redirect to another

C: The reason it comes to mind is because it took a really long time to solve the one problem. So that's why it jumps to mind right away. So the problem was, I was a graduate student sort of in the middle-end of my graduate school career. And I had accidentally discovered a new reaction

A: Ok

C: So I was working on something and out popped this molecule that I was not expecting. And, um, that was very exciting. And then, but it's not that interesting until I figure out how it's happened.

A: Uh-huh

C: So question. My problem was, where did this molecule come from?

A: Right

C: (inaudible) and what. That's kind of the main question that I ask in my research all the time. I study mechanism. So how did this molecule form, is typically my question

A: Ok

C: This one jumps out because it took, it took a long time. So typically what we do to solve that kind of problem is we come up with a series of possible mechanisms. So you just write down any possible idea of how you could possibly imagine this molecule is formed. And usually you can think of 5 or 6 right away, and you ask you friend can they think of any ways, and they'll think of another one. And you'll end up with a list of you know 3-10 ideas.

A: Uh-huh

C: And then you typically, and this is what I normally do, I typically would go through and design experiments to try to eliminate the possibilities one by one until I am left with only one. And since I've already listed every possible thing I can think of and I've eliminated them all but one, then I conclude that last one is right.

A: Uh-huh

C: What made this one weird, and is like my example that I jump to, is that I couldn't think of a way. I couldn't think of one way.

A: Oh

C: That it could have happened

A: Ok

C: (laughs) and so I couldn't follow my normal procedure.

A: Right

C: I just sat there and I couldn't think of a way. And I asked my very famous accomplished PhD advisors, and they couldn't think of a way, and every time a seminar speaker came to town, I asked all my friends, every time I talked to another chemist who was visiting, I would ask them. And there was no way. Where did this? Everyone was just like "are you sure this is your molecule? I don't believe you. This couldn't have happened."

A: Wow

C: And so I eventually, and you know obviously during all this time I'm trying to think of a way, and I'm also retesting a thousand times to be sure that this really happened. And it really happened.

A: Right

C: And finally, I decide that I'm going to. … finally I decide that. Ok, I'm an experimental chemist. I do experiments to figure out what's going on. I just explained, I come up with all ideas and then I do experiments to eliminate them. But I couldn't think of an idea, so I couldn't think of an experiment, so I decided to turn to computational chemistry or theoretical chemistry, which is a whole field in itself, but I went down to the basement, and I learned this whole technique of computational chemistry that I did not know how to do, where you can test, um, you can do calculations to see if molecules are reasonable. And so I learned how to do this. And then so I started trying to test totally off the wall hypotheses, but now I was doing it on a computer, so that was okay. I could try totally crazy that seemed like a really wrong idea, but at least I was trying something

A: Uh-huh

C: So I was trying crazy ideas that were really definitely wrong, but I could try them through the computer.

A: Right

C: So I tried these things, and the computer is telling me like "no."

A: (laughs)

C: This is wrong. That's totally wrong. This is totally wrong. But in that process, um, I was able to visualize in 3D. Oh. So another thing I tried to do while trying to think of an idea, um, I made physical models

A: Uh-huh

C: Using model kits, and tried to look at it and move them around. And I still couldn't think of an idea. And I even went over [to use] like a $1000 model kit that was better than any other model kit.

A: (laughs)

C: On the floor trying to do it, and I still couldn't do it. And then by using the computer, which had a 3D, you know it was a modeling, a physical thing, a digital thing that you could look at that had (inaudible). Even by trying to make my terrible ideas, I slowly was able to think about it differently.

A: Ok

C: And through that I finally started to think of slightly more reasonable. Every slightly more reasonable ideas

A: Ok

C: That I was one by one on the computer. And the more I did that, the closer it got me to imagining an idea. And eventually, I saw on the computer, while I was playing with it, I saw, "oh. What if this other bond breaks first?" That I never thought that could be the first bond to break. But I could see it, because I had this visual representation, and I had tried breaking every other bond at that point, and every terrible idea, and I just tried so many terrible ideas, until finally I saw it on the computer. And I was like "ah, that one." And I started doing calculations on that. And it was actually kind of reasonable.

A: Uh-huh

C: And doing calculations. And I showed on the computer that it, that it actually did this one sort of weird, unprecedented idea actually could explain the crazy molecule that I got

A: Ok

C: And so that was very exciting. And I finally, I could just write down, for the first time I could write down something that made sense. One idea that made sense, which is usually the first step. And it took me a year to get to "write down one idea that makes sense."

A: Right

C: But I ran upstairs to my advisors

A: (Laughs)

C: "I wrote down an idea that makes sense!" Like I could not (inaudible) I didn't even have any evidence yet, but I had

A: Right

C: Makes sense. Um. And. Yeah. That was the triumphant moment. And then I went back and designed, um some experiments that could you know possibly rule. Several experiments that could possibly rule this idea out.

A: Ok

C: And they could. All of them were consistent with my one idea that kind of made sense. And

A: Okay

C: And that was my solution to the problem in the end. Um, and it was, yeah, it was different because I usually think of a bunch of ideas that make sense and rule them out one by one, and this was really hard to come up with the one idea that made sense, and then do some experiments to show it was reasonable

A: Okay. So how, how did you end up starting? How did you end up getting this molecule and knowing that it was a weird molecule in the first place?

C: Oh boy, I mean, the first time I did it, it was an accident. So I had a whole other hypothesis. A whole plan. I designed a molecule that I had a particular job that I wanted it to do. Again, it was sort of not a mechanism. I'm interested in how do molecules form. I was curious about how a different molecule formed, and I had this idea that if I made this molecule, then it would either do a or b and that would tell me, um, you know something about the mechanism, you know which bonds break in what order. But it did not do a or b, it did (gesturing)

A: (laughs) right

C: And that was (inaudible). So I had planned it out as, I had designed this molecule specifically to report on the mechanism of a reaction

A: Ok

C: First that'll happen, if that breaks first, that'll happen. Neither of those happened. And so, and something just completely unexpected came out.

A: Right. … Okay. Um. And, so how did you, you said you did several experiments at the end to try to break your one idea. Um, how did you decide that you had sufficient to say that "yeah, no, this weird new thing is actually right."?

C: Yeah. It's funny cause that's usually what we do, is say "well, we ruled out all these other things."

A: Right

C: This time, no one could think of any way for it to happen. So it was different. And you know, we never, we always say in my field you can never prove a mechanism. You can only disprove one.

A: Right

C: And even though I do, I'm not, I'm pretty confident there's probably something wrong with my mechanism, it can't be exactly that. But I also think it's a good step forward from having no idea where that comes from.

A: Right

C: Um, and so that's how. That's what I know. That's what I feel satisfied with. That my model is better than the complete lack of model that came before.

A: (laughs)

C: Not that I have achieved enlightenment and this is exactly definitely. I have come up with a model that is consistent with my data, and is exciting. But I cannot say that actually this is what happened. I do not say that in the paper.

A: Okay (laughs). Um, so you've used the word model. Which turns out is a word that comes up a lot. So can you say a little bit more about what "model" what models mean to you.

C: Uh, yeah. I mean, in chemistry we can't see molecules, usually. Um. And that's all I care about.

A: (laughs)

C: And I basically am only, in terms of my thinking and talking about these things, I'm only working with models. Um. So there's the very physical models of, you know sitting on my friend's floor with his baby playing with the model kit, there's one model. Or my computational model, of course. When I just used the word model, I meant my idea of, um, which bonds break in what order. I consider that a model for the mechanism of the reaction, because I envision that truly the atoms are doing something that we can never see or know perfectly, and all we can do is describe it the best we can.

A: Ok. Um, let's see. I have a list of questions… Um. So, what do you think were critical decisions that you made to solve that problem?

C: Um, I think, well it was really important to um, to try a new approach

A: Uh-huh

C: A new technique – going downstairs to the computation chemistry lab was a turning point

A: Uh-huh

C: So, yeah, I think that was an important decision. Um… let's see. What else? … the main decisions. Um, I think there were a lot of little decisions once I was in the computational chemistry lab

A: Ok

C: Let me try this now, let's try that. Or this is worth trying. (laughs) which a lot of people, you know might not have thought it was worth doing.

A: And so by those decisions, those are like the "oh, let's see if this is the bond that breaks?"

C: Yeah, let's even. I went down to the computational chemistry lab to calculate just the worst ugliest molecule that was definitely wrong. And the decision to do that anyway

A: Ok (laughs)

C: Was really important. And then the next decision of ok, now let me try this ugly terrible molecule that can't possible exist that is slightly less sad than the previous. Going down that path is what got me to finally having an accepted model.

A: Uh-huh

C: Of being willing to put in time for, time and effort on something that was clearly not the answer.

A: Right. Um, so speaking about time and effort, how did you, I guess, decide that this was a problem worth pursuing in the first place?

C: Yeah, I mean that was a really big question that was part, you know, part of this conversation the whole time. Should I. Right, cause I was trying to study "how did this carbon-carbon bond form?"

A: Ok

C: Forming this carbon-carbon bond is useful for synthetic chemistry. We can build bigger molecules. How does this carbon-carbon bond form? And the molecule that I made did not form the carbon-carbon bond

A: (laugh) ok

C: It rearranged itself. But it didn't actually put two molecules together, which was what I was trying to do (laughs). So you might have said, ok, you failed, move on to something else. But I was into it. I was excited about it because, because it was so unexpected. Because everybody's reaction was "you're sure that's what happened?" because that was my own reaction.

A: Right

C: The very fact that I could not figure out, as a mechanistic chemist, it was so exciting to me that I had a reaction that I had no idea what

A: Yeah

C: So the fact just for me that it was, I want to study mechanism, and it's rare to have a mechanism that is so unknown. And that whatever the answer it is, it can't be any of the normal stuff that we're used to. You can think of all of the normal stuff, so whatever the answer is, is going to be really cool.

A: Right

C: So my eventual mechanism that I proposed for this is cool. It is an unusual unprecedented mechanism that no one would have thought of for a while

A: Uh-huh

C: And it does. And it is the only way we can think of to explain our data. So I think it paid off. So yeah, for me I think it. There was no, it was too weird to let it go. But I let other weird stuff go. Like one time I made this really weird like dark blue stuff when it was supposed to be colorless, and I was like "whoa,

what's that color" but I only gave it like two hours of my life before I was like "you know, what I think have the general idea of what this is going to be and I'm not that interested."

A: Uh-huh

C: But this other one because I couldn't think of a boring answer, I knew that the answer was going to have to be interesting. …

A: So in the case of the dark blue stuff, you were able to think of a something that it was that was boring, so then that wasn't…?

C: Yeah, like I'm sure someone might be into studying that, but I, I was like "ahh, it's probably the, it's know that carbo-cations can have a dark color, and it's probably, it's probably just a slight variation on that." And so I didn't want to go down there. I or anyone else didn't really care if that's what it was.

A: Right

C: So yeah, because I could think of something, I didn't really want to do it.

A: Right. Did you ever end up solving the other question of how the carbon-carbon bonds formed?

C: Yeah, um. Well, so, I mean solving is you know. For me science is always, by definition every time you solve a problem you create new problems

A: Sure

C: So I had come up with you know, a pretty, um, satisfying solution about that carbon-carbon bond thing already.

A: Ok

C: Inspired me to try this new molecule that would kind of tell me more about that direction of the problem I had already solved because I had kind of, I had definitely solved the problem there, and came up with an "ok, this is what's causing that. We got it." And the question was like "oh, if this happens, you know, what, how often is this happening in the other related systems" or something.

A: Ok

C: Let's test for this thing that I already found more frequently. And so that was sort of the motivation for making the new molecule that ended up doing the weird thing. And so I though a weird rearrangement was more interesting than the original problem, and so the short answer is no, I did not ever go back and do what I was originally trying to do.

A: (laughs). Okay. Um, and so what are the implications of your new reaction?

C: Yeah. Um, so I think. So it turns out. So I thought I was studying making a carbon-carbon bond, which is great for making molecules. It turns out, that I discovered a new way to break a carbon-carbon bond.

A: Ok

C: Which is actually a lot harder to do than making one

A: Huh

C: And it's also really important to be able to do in synthetic chemistry

A: Yeah

C: And it's so hard to do that people.. don't. Making a carbon-carbon bond we have ways of doing it, and some of them, we might argue that some of them are inefficient or create a lot of waste or you can't control them very well, but we have a ton of.. That's what an organic chemistry class is. (inaudible)

A: Uh-huh

C: Breaking a carbon-carbon bond there really just aren't. You don't learn those in O-chem. And the reason is there just aren't really ways that we can confidently break a carbon-carbon bond without just burning the whole molecule up.

A: Ok

C: My reaction, turns out, is an example of very specifically breaking one carbon-carbon bond using a catalyst.

A: Ok

C: And I don't, and so it's among just very few examples of being able to do that. And so that is something we want to be able to do more. And so it'll be several steps between my reaction and something that can be used for anything, but (laughs), it is a step towards being able to break a carbon-carbon bond on purpose where you want

A: Ok

C: When you want to, in synthetic chemistry

A: So do, do you know, are you or are other people working on that?

C: Well, that's kind of the thing with being a graduate student

A: Right

C: Um, as you know now that I'm a faculty member, I have my own research projects and I didn't, I didn't really want to, nor is it considered appropriate in my field to take on a project that I did work on as a graduate student. Um, so I sort of abandoned that. I did have undergrads who had been working with me that I left behind who were still sort of working on that project after I left. But, you know I put it out there in the literature

A: Yeah

C: And there are other people out there citing on it, (inaudible) and I do think that they could think of something down the line as other people try to follow up on it. I (inaudible) mechanisms of catalysts, but not that exact direction.

A: Yeah. Okay. … Um, you already, you basically answered all of my questions in your own description, so I don't have to ask a lot of them, which is great. But that gives us time to maybe have you talk about one of the projects that was maybe more typical, so that I can see how your thinking works in those situations too.

C: Hmm, okay. Um, yeah. Pick out which one I want.

A: (laughs)

C: Um, debating between the direct predecessor to that project or, I don't know I kind of like that one it's kind of clean. Um, or I could do, I feel like my postdoc project was very carefully thought out but really complicated

A: (both laugh)

C: And so, um, I think it would be easier to narrate. Yeah. I think I'll do the project that was, and besides it flows. So the project I did immediately before that, that led into it. This one I had a very clear research question that defined. Which was, we have this catalyst. It takes these two molecules and puts them together. How does it work?

A: Ok

C: And that's the kind of question that I like. Um, very similar to the other one. How did this molecule happen?

A: Right (laughs)

C: Like what, what steps occur? And, um, this time there was a … the answer ended up being a little bit surprising, which was great. Um (laughs). So in this case, I did, um, just draw out a few options, hypotheses

A: Ok

C: About how it could work. And there were some out there in the literature

A: Ok

C: There were maybe three or four different research groups around the world working on this exact process or closely related ones, and people had proposed mechanisms, and no-one had ever really dug in. You know, they just. It's often acceptable in the field to just write any one mechanism that makes sense and is consistent with your data

A: Ok

C: And --- proposed mechanism without any direct evidence. And that's okay

A: Yeah

C: .. their ideas about what it could be.

A: Uh-huh

C: So there was kind of one general accepted idea, and then some sort of various subtle tweaks to that idea. So the general. Okay, there's these steps. There's a platinum catalyst. The platinum catalyst comes in and it's the key step, we called it a C-H activation reaction because it would break a carbon-hydrogen bond and then make a carbon-carbon bond.

A: Uh-huh

C: But breaking the carbon-hydrogen bond is supposed to be the hard part, so we called it a C-H activation. So the idea is a platinum comes in and it breaks the carbon-hydrogen bond and then the other molecule comes in and then two carbons can bond and then -- come of, and then the catalyst can ---. And that was generally the accepted mechanism that multiple people have published as "okay, we think this is what's happening.

A: Ok

C: And people were kind of like "oh, well, you know, when it breaks the bond does it break it right in half or kind of from one side?" You know some questions like that were out there

A: Ok

C: And I was interested in getting at that. But also there were some weird, there were some mysteries. Because not all of the, the chemistry wasn't that good. Like it wasn't a great reaction. No one's using this reaction for anything. We'd like it to be better, and improving it. That was our motivation for trying to study how it works.

A: Ok

C: If we know what's happening we could improve it.

A: Right

C: So it doesn't always give you the right product, or it requires high temperatures, or ---. It just really could use some improvement before anyone would want to use this for anything. And. .. Our, so I started. Even before doing too many experiments I was a little suspicious of this standard mechanism

A: Ok

C: So what I did was wrote out the mechanisms that people had and some variations thereof. And then I started doing a few experiments. I wanted to study the rate of the reaction. That can tell us a lot about which steps are happening, depending on which step is going faster or slower … reaction.

A: Uh-huh

C: So I started just running the reaction, getting some basic data on it. And there's some standard control reactions that people tend to run in my field, and also that I just thought of that I wanted to do. Because good to check, and make sure. You know, what if you run the reaction and leave out one of the ingredients, does it still work

A: Uh-huh

C: And stuff like that. And so um, a similar reaction can be accomplished with, instead of using the platinum, using just an acid

A: Huh

C: And so I ran the reaction with acid instead of with platinum. And I got the same result with platinum or acid

A: Huh

C: And then my hypothesis became that the reaction was not platinum catalyzed after all. Despite [the model in the literature]. The platinum was actually not involved

A: Interesting

C: We knew that acid could do this too, but no one had done them exactly side by side and showed that they do the Exact same thing

A: Yeah

C: Once I saw that, I needed to design some experiments to try to rule out. Now I really had two. Is it platinum catalyzed or is it acid catalyzed.

A: Right

C: And I came up with a series of experiments that could rule one or the other out. So even just that first experiment, so "yeah, they do the exact same thing with or without the platinum" was a suggestion that the acid was responsible.

A: Right

C: So then I, I did a few more experiments. And I think for me, um, what I ended up doing at the end of this project was. Oh I, I put in a base with the platinum. That was a key experiment. So a base that would stop any acid from doing the reaction, but would not stop the platinum.

A: Right

C: And it did stop the reaction.

A: Okay, yeah

C: That supports the idea that. But again it supports, it does not prove it. That it was an acid that was doing the reaction. But who knows, maybe once I had that result, we can have a bunch of other

reactions. Like okay, maybe this base did stop the platinum. Or what if the .. need a little bit of acid but the reaction really goes through the platinum.

A: Right

You know, all different. You can always come up with new, um, new ways of explaining the data.

A: Uh-huh

C: And so my clincher experiment that time was, and this is how, this is sort of the thinking that ended up leading to that other project. Um, throughout this I had also tried a bunch of variants of the two. I'm saying it brings two molecules together, but I --- different styles of that molecule or different styles of that molecule and see how changing them affects it. And so, um. Another piece of evidence that acid was involved was if I had a very electron rich thing over here, and that's the thing that I think actually needs to get protonated

A: Uh-huh

C:.. mechanism. I have that the more electron rich, the more basic this is, the better the reaction is, and

A: Ok

C: It was acid. And then my final. And then at that point, if it was acid, the thing I needed to answer was, I didn't add any acid to the platinum reaction.

A: Ah-hah

C: So if it's acid doing the reaction, where's the acid coming from?

A: Right.

C: So I had to come up with a mechanism for. My ultimate mechanism was that the platinum produces acid. That's it's job.

A: Uh-huh

C: And --- the reaction. So I did a series of experiments to support that. … showed that if … add. By changing the substrates, um, I decided that, or I hypothesized that the acid came from one of the substrates. The platinum would grab a proton off of that and make an acid out of it. So if I chose a different substrate that did not have a proton right there, it should not do the reaction with platinum, but it still should do the reaction with acid. And that turned out to be correct.

A: Right

C: So that reaction, with, if there's no proton right there. Does not work anymore with the platinum catalyst. Does work with added acid.

A: Uh-huh

C: Also does work, what was really cool. I put it in with the platinum which doesn't work, and I added a little bit of the other substrate that does have the proton there, which should produce some acid and should make it all react. And it does.

A: Oh that's cool.

C: Yeah. So a bunch of different experiments just designed to keep. One experiment is never enough.

A: Right

C: So having all of the. By the time I had gathered all that evidence, I pretty convinced that this reaction was catalyzed by acid, which was produced by the platinum carrying off that proton. And then that answers why the reaction wasn't that great, because acid's not that great

A: Ah

C: At being controlled, or producing the product…

A: Cool. And so, you've talked some about like, the data that your model explains. Can you say a little bit more about what the type of data is that you have?

C: Yeah. So I mean. Right. The data I'm referring to are, yes, I. I observed yields of this reaction. I observed the identity of these chemical products under different conditions. So if the, the, you know. The data being "okay, this reaction works well under these circumstances and doesn't work well under these circumstances, then my model is the only one that was left standing that is consistent with all of them."

A: With all of them. Okay. And, in either. Yeah, I guess in either of these projects that you've talked about, what challenges did you encounter?

C: So many

A: (laughs)

C: Well, so for this one, I guess there was, there was sort of a --- challenge [about how to present a model that was different from the previous literature - details redacted].

A: Right

C: So that was interesting to navigate. Um, because, it is part of science that we're always, um revising our theories and models, and that of course everything we publish now is going to be found to be at least a little wrong some day

A: Right

C: So yeah, that was one tricky part of that project. Um, and, um. Yeah, and I guess another was trying to sort of, sell the paper and tell the story in the end

A: Ok

C: Because it's seen almost as a negative result, and people aren't (----)

A: Interesting

C: Like, oh, "we thought you were working on platinum catalysts. We'd be more interested if it was platinum catalyzed." And a lot of people wouldn't have taken the time to do those exp. One they notice that it might not be platinum catalyzed, they might have given up and moved on. And not gone through with showing that clearly it was not platinum catalyzed. But I thought that was important

A: Right

C: And I do think that's important. Um, but it's not the most glamorous, like I did, I succeeded, I figured out how the platinum catalyst worked and then I made it a million times better and now I'm rich! Like that's not. the story. What's happening and so being able to just go with what did happen and present that as, um, a useful advance is challenging.

A: Yeah

C: Um, but yeah, in terms of the other. You know the actual process of figuring things out, um. I mean, I remember it, and maybe I'm misremembering it. But I remember it as being really fun. I think it was, the surprise of realizing that it was acid catalyzed was ---. What do I do with this?

A: Yeah (laughs)

C: But that process of now having a really clear question: is it acid, yes or no?

A: Uh-huh

C: And if so, where does the acid come from? Being able to design experiments to figure that out. --- I mean, there's always the day to day. You know things break. I've definitely exploded some --- by accident along the way

A: (laughs)

C: Had to repair equipment, and um, you know, deal with all of that (laughs) along the way, but I think the main arc of figuring it out, um, that was the fun part.

A: Cool. Um. So, thinking a little bit more generally, um, and about, what experts, how experts think in general. Um, or. Okay. Thinking about students that you've had, or undergrads you had when you were a graduate student, what, have you noticed difficulties that they have in their problem solving process?

C: Yeah, um. Yeah, so I haven't. I was thinking about whether I should give you examples from my current group.

[Discussion of current student work redacted for privacy reasons]

Biology postdoc (1)

A: We're trying to find out how experts think and solve problems in their fields. So we're doing a bunch of interviews with people about how they solve problems in their research. So what I'd like you to do today is think about a research problem, maybe the paper you just submitted, and walk me through all the steps that you took as you were solving it. So.. " I did this.." and particularly think about the decisions you made. And so..

B: Okay. So the paper --- is, so I study aging. And I study the way that different environmental factors and in particular social interactions can influence the rate of aging. So is study this in worms. And what we knew at the time when I started this part of the project is we knew that C. elegans hermaphrodites have their lifespans shortened by the presence of males. And we knew a little bit about how that worked. We knew that male pheromones, sperm, and seminal fluid all contributed to that. Um. But, and we knew some genes that were involved. But that was kind of the extent of it

A: Mm

B: And we knew that it didn't matter. If the males were around for a long time, it didn't matter if the hermaphrodites were fertile or not. So you can sterilize them and they would still succumb to this what we call male-induced demise. So we knew it wasn't just because they were having a lot more progeny

A: Right

B: But what we didn't' know was more kind of the dynamics of it, and really what was going on. So when we first did the project, it was, the initial findings was that males were around for a really long amount of time. But that's not really what happens in nature.

A: Ok

B: Because in nature, the males are pretty rare for C. elegans hermaphrodites. They're like less than 1% of the population, and here we were putting them in a situation where there was like 50-50 males and hermaphrodites

A: Ok

B: So that probably doesn't happen that often. So that probably doesn't, we weren't really looking at what really happens physiologically in nature and how they may have evolved to respond to that. So what we did was we developed an assay that we developed to ensure that mating happened, but that we could get it down to a really brief period of time. So they'd hang out for 2 hours.

A: Uh-huh

B: And we'd know that they mated because we could fluorescently label the male sperm and see that it got into the hermaphrodite, so we were like "okay, the mating happened." And that was. That was an important thing to figure out how to do. Because they other ways you can track whether mating happened or not are all things that are like three days later

A: Ahh

B: Because normally hermaphrodites only have hermaphrodite only progeny, but if they mate with a male, 50% of their progeny are going to be male, so you can use that to just be like "okay mating happened."

A: Right

B: But it's way after the fact, so it makes doing the experiment really laborious.

A: Right

B: Because you've got to like track all of these. So figuring out how to do that was really important, and really like, fixed. Fixed some issues for us. And so we found is that if the hermaphrodite. If that brief period of mating happened when they were young, there was no impact on their lifespan.

A: Really?

B: So they had a perfectly normal lifespan. But if it happened when they were older, their lifespan was shortened. Not to the same extent as when males were around for a really long period of time, but it was still significantly shortened.

A: Huh

B: And we can do this multiple times, we could see that. And then so we had this data, and we're an aging lab, so we thought "oh, it's cause they're older." Of course. As animals get older, they're less stress resistant. But we didn't know for sure. And so we thought about what else might be going on, and maybe things were a little bit different with this brief period of interaction as opposed to this really long one. And we kind of talked about it to a lot of different people and heard what they thought. People outside of the aging field, that weren't so in their heads about "oh, it's aging, aging, aging."

A: Uh-huh

B: And a couple of people brought up, "well maybe it's that they are no longer self-fertile."

A: Oh

B: So what hermaphrodites do is they have, they make sperm and oocytes, but they have a limited number of sperm they can use to self-fertilize. They run out as they get older.

A: Okay

B: So in addition to getting older and being more stress resistant, they transition from having sperm and oocytes to having only unfertilized oocytes.

A: Interesting

B: So, so you know, that was brought up as another possible explanation. So okay, well how are we going to figure that out? And fortunately in C. elegans there are so many great mutants, that there are mutants that feminize the worms. So even when they're young and healthy and stress resistant, they only ever have oocytes

A: Ok

B: So then I performed the same experiment, but I used these feminized worms. So I looked when they were young and when they were older. And what I found is that even the young ones, when they didn't have self-sperm, and they weren't self-fertile, they succumbed and lived a shortened life span.

A: Interesting.

B: So that experiment really helped us be like "okay, it's not their age." I t has something to do with their germ line and their fertility. And then we kind of went in and tried to figure out a little bit more details about what exact aspect could that be. Because we knew when they're self-fertile, they have oocytes, they have sperm, they have developing embryos. Which one of those things was the important thing? So we knew if they were sterile, if they didn't have any germ line cells, they succumbed. If they didn't have sperm, they succumbed - if they just had oocytes. If they had sperm, but the sperm couldn't fertilize their oocytes, they were resistant.

A: Ah

B: So it wasn't having embryos, it was something about the sperm

A: Huh

B: So then next. I kind of turned the problem around a little bit. Cause here we had found the sperm was necessary, and I wanted to know if it was sufficient.

A: Ok

B: So then I used another mutant that was a masculinized one. So then, they looked just like normal hermaphrodites, and they have a normal soma, but their germ line, they only ever made sperm. And so those were resistant, and they were resistant to, they lived a normal life span even if they mated when they were older, unlike the old wild-type worms that had run out of self-sperm. So that told us it was both necessary and sufficient for this protection. And then there's a signaling pathway that um helps to detect whether or not sperm is present, so I tested that as well, and it seems to be going through that signaling pathway. And um, and then because I have an evolutionary biology background, because really this project, what I was really excited about was better understanding what might happen in nature,

A: Uh-huh

B: I then asked if other species had a similar response

A: Ok

B: So most species of worms are female. True females. They don't ever have self-sperm. Um, but there's a few other hermaphrodite ones. So we tested another hermaphrodite one, and that had a similar response.

A: Interesting

B: So it was like c. elegans.

A: Uh-huh

B: So I guess in terms of like specific problem solving, what helped me was just talking to other people about it and getting like different perspectives on it. And then like reading the literature a lot, and trying to figure out. So a lot of these germ line mutant papers are from the 80's you know. and so people still use them, but figuring out what's really available and what's the best one. Thinking about it and drawing out, drawing out models and where there were holes in the model. That really helps me too.

A: So can you elaborate on a model?

B: Yeah, sure, so I guess one of the things, like at the beginning. You know I knew young hermaphrodite, and then I'd have a little arrow

A: Uh-huh (both laugh)

B: Would be resistant. And like Old hermaphrodite, little arrow, sensitive. Be like, okay this is what we know, looking, young hermaphrodite, old hermaphrodite, and what's different about them?

A: Uh-huh

B: And before I had talked to other people, I was kinda thinking "you know, maybe if I use a really long lived stress-resistant hermaphrodite, that'll do it, and they'll be resistant to the males for longer." But before I actually got to that experiment we had already talked to some experts, and so, so that helped me narrow down like okay, so it's something to do with their fertility status. So then I could draw like "young hermaphrodite, old hermaphrodite" and have a list under there like. Oocytes, sperm, embryos, and I could kind of like cross some of those off

A: Uh-huh

B: A little bit. So I guess it's a little bit less of a model and more of an elimination game.

A: (laughs)

B: Yeah, um but just kind of thinking through what are all the possibilities there might be to explain this, and then slowly going through and figuring out what experiments will eliminate as many of them as possible in kind of one go, so then I could help to narrow it down.

A: Uh-huh. Um, and so were there any particular challenges during this?

B: So one big challenge was, so the. The other species that I used, C. briggsae, they were kind of a pain to work with.

A: Ok

B: And so you know just like a challenge of figuring out different ways to just do the experiment in that species. So the problem was that when you do a lifespan assay, you have the worms and they're on a plate. And they're supposed to just stay on the plate so you can count them for the whole three or so weeks that they live. And C. elegans are really well behaved and they stay on. But certain strains don't.

so this particular strain, this C. briggsae strain, I don't know why but they just crawl off the edges and they kind of kill themselves

A: Oh no!

B: Because they leave the agar and they dry out. So they were just. They just were constantly doing this.

A: Oh no

B: And so you get to the point where you have 10 animals left, which isn't enough to really have like a good experiment. So I tried a couple different ways to solve it. I asked people who had worked with the worm before. I read a little bit about it, there wasn't really a lot that had been talked about before. Somebody suggested like turning your plates upright instead of upside-down, so I tried that.

A: Huh

B: There, apparently you can put something that they really hate around the edges. I didn't end up trying that because it seems like a big pain, and I was also worried about like what if that affects the results, so I didn't do that. In the end I ended up just trying to do as many worms as possible.

A: Ok

B: And combining multiple experiments, and then I ended up just switching to a different strain that did it less. Because it was just. It yeah. It was hard to really get them to kind of behave themselves. I suppose if really needed to rely on that very particular one I probably would have exhausted the possibilities a bit more, like using that substance they didn't like. You can do lifespan assays in liquid

A: Oh

B: They're kind of a pain, but maybe I could have done something like that. Yeah. I think maybe those. Maybe like changing the composition of the agar or something, who knows.

A: (laughs)

B: So maybe I could have tried some of those things, but in the end I kind of bailed on that one and switched over to one that was easier to work with because it just, you know, I didn't. it wasn't worth the hassle of it when I had other options.

A: Right. Um, so you also mentioned like needing more than the 10 animals left. So how did, when you're setting up an experiment how did you… I guess walk me through the details of setting up an experiment.

B: Okay. Yeah. So for the lifespan assays? Um, so the way that we do the lifespan assays is you age synchronize the worms, so what that entails is getting the parents, having them lay eggs for a defined period of time like 3-4 hours.

A: Okay.

B: And then you pick off all of them and then you just have the eggs sitting on the plate. So then you know exactly how old those animals will be because you know exactly when they were laid. And then in 3 days they become adults. And then what I would do for these assays is then I would mate them with these males.

A: Uh-huh

B: And then I would continue, I would pick up all the ones that had the fluorescent male sperm, so that had successfully mated

A: So you're actually going in there and picking them up?

B: Picking them up. Yeah, you're literally picking them up. And then I tracked them for the rest of their lifespan. So those same individuals, I'll put them. I'll usually have like 3 plates of 30, and I'll just, I'll keep transferring them every day and tracking them and seeing if they're dead or alive

A: Okay (laughs)

B: And it's important to check them frequently because um, you know they only live for three weeks. So you kind of have to know when do they start dying, when are half of them dead, and when are all of them dead? Are kinda of the main points that we care about a lot, but it's nice to have a good shape in your curve.

A: Uh-huh

B: The other reason it's important to check them every day or every other day is that, um, they have progeny all the time.

A: Ah

B: And they lay like thousands, hundreds, of eggs. And in three days those become adults, and you can't distinguish them from the ones that you actually care about. So you need to constantly be moving them away from their progeny

A: Okay

B: so that you can track the ones that you actually want to track. Um, and you have to, you when you're tracking them you have to make sure, you have to make a decision about how you think that they died. So we care about the ones that die as a result of aging, or like "natural causes." But other things can happen to them along the way. They can, really awful things happen to them. They can have what's called a vulvar rupture where their intestines go outside. And we don't count that as a normal death

A: right

B: They can do this bagging, or matricide thing, where they aren't able to lay the eggs and the progeny hatch inside of them

A: oh

B: Yeah, so really terrible things, and we don't consider that true aging. It's a separate event, so we censor it from the lifespan. You have to learn how to make those decisions.

A: Uh-huh

B: Um, the other thing that we do whenever possible is to, um, blind the assay. And this is really important because we can put a lot of bias into the experiment. Because we are kind of making those judgement calls. Is the worm alive? Is it dead? As they get older they don't really move a ton

A: Oh, okay

B: So you have to poke them a little bit, and see if they move their head a tiny bit. And you can imagine that if you really want the worms to die more quickly in a particular condition, you can be like "oh, I don't really think he moved."

A: Right

B: So whenever possible we always blind the conditions. Sometimes you can't, just cause it's easy to tell the difference

A: Right

B: Um, yeah, so then you just you have a pile, you have all the data and it tells you when each worm died. And you're able to build, they're called Kaplan-Meyer survival curves. They're just little like staircase looking curves that tell you how many individuals died on any given day. And then we can perform different statistics on them to figure out if, um, if one batch of worms died earlier or later than another.

A: Okay. And um, in all of that you described, how much of that was established protocol, and you're just, this is what is done and how much is you're making decisions along the way. I know you're making decisions about if it's alive or dead…

B: Yeah, so it's a pretty standard protocol. There's some variability in the field about how you do the egg lay, that kind of stuff, but it's pretty standard. In other projects like I've made decisions about, like you can use RNAi knockdown to knock down gene expression. Some labs make the decision that they want to start that from like all through development and everything

A: Ok

B: And then the knockdown will happen throughout the whole development and adulthood, and then see what happens to lifespan. I don't like doing the experiment that way. People have different opinions on this. I like to start it when they've reached adulthood, and the reason I like to do that, and the reason I made this decision is. Because I'm studying aging, I don't really, I don't want to study development. And what I don't want to happen is to have a knockdown where it affects them developmentally, and maybe they don't have a certain population of cells or the population of cells are behaving in a very different way because they changed during development and then that's why they're living longer. I care about genes that are acting when they're adults.

A: Right

B: And so that's why I start the RNAi knockdown when they're adults. So that's kind of why I made that decisions. So just kind of thinking about what potential things could explain a result that I'm getting

A: Right

B: So that allows me to eliminate changes during development as an explanation.

A: Right. … Cool. Let's see. In this project what do you think were critical decisions that you made?

B: Hmm. … Let's see. Um, well one decision that I made. I don't know how critical it was. Hmm. Critical decision. I guess they all feel kind of critical. I mean, one decision that I guess I made that I didn't feel like I made in the best way was I did an RNA-seq experiment to look at the gene expression for the young hermaphrodites and the, that had mated with males and had not, and compared them to the feminized ones. And I made the decision to do that RNA-seq when they were already adults,

A: Ok

B: Whereas we had a collaborator that was working on this project as well, and they at the same time made the decision to do it just before they became adults. They made the better decision than I did. Um, I made the decision to do it when they were adults because I thought well, that's when we're doing the assay, that's when we're seeing. You know the difference that we have between these is an adult difference. Um, whereas they thought well, you know, probably there's already going to be differences between these two types of worms before they even reach adulthood and maybe we can figure those out. The reason that their decision ended up the better one

A: Uh-huh

B: Was that my experiment, I had these wildtype worms that were having a ton of progeny, and then these females that weren't having any progeny. And I was trying to compare them to each other.

A: Ah

B: And the majority of what I saw when I compared them to each other is that a ton of genes associated with early embryo development and fertilization and those kind of things that at that point I was pretty sure weren't important. Were the dominant things.

A: Uh-huh

B: In my experiment. So guess that was a critical decision that I made incorrectly (laughs)

A: Sure (laughs)

B: But I kind of had to, you know I had my reasons for doing it the way that I did. And had I had more information, or like, hindsight is 20-20 then I would have made a different decision.

A: Do you think that if you didn't have those collaborators, you would have done the experiment again the way they did it, or would you have just said "I don't see the differences"

B: Um, we definitely saw them. Yeah, I guess I would have gone back and maybe changed the experiment a little bit and tried to do it in a better way. I probably still would have stayed with adulthood. Because had I not known that you could detect these differences while they were still developing, I would have still thought that I still want to look at them when they're adults because that's when I know there's a difference between them

A: Right

B: Um, what about like, you know maybe I would have, um.. at the same time I was doing that RNA-seq experiment I was figuring out that like fertilization itself didn't matter.

A: Ok

B: So I probably would have done a few more experiments to use different sperm mutants, and used a mutant where there was never going to be any fertilization that was happening. So they'd have the sperm and the oocytes vs. the ones that just have the oocytes, but they wouldn't have any embryos or any fertilization, so that would have eliminated a lot of those differences, which made them

A: Uh-huh

B: So I probably would have gone back and done the experiment that way. I guess we were kind of thinking that we might want to do the experiment that way, but at the time I didn't know, I didn't have all the data to know whether I should do this expensive experiment in kind of an unusual, using all these unusual mutants

A: Right

B: Um, and we thought, well, who knows how long it's going to take to get the RNA-seq data back. Let's just do the experiment the way that we know we get the expected result in terms of lifespan. But maybe if I had waited a couple of months of if I had decided to redo it I would have done it a different way.

A: Ok. Um... Oh. Well, I guess how did you decide to do this particular project? Why was this a question you decided to approach?

B: Mmhmm. So when I joined the lab, I was really interested in studying how evolution has shaped evolution and lifespan. And, I kind of started working on that, but at the same time there was another postdoc who was working on this male-induced demise question. And he wanted to know whether it was evolutionarily conserved. And so I started working on that, and it just became. I became more and more fascinated by the problem and the question. And I guess the reason that I particularly wanted to study this aspect of it is that I liked that it was, it was looking at the problem in a way that was a little bit more like what could potentially happen in the wild.

A: Uh-huh

B: And by doing that it also allows me to ask some evolutionary biology questions in the future, I hope, or do to do more of it. Because we are trying to better mimic what happens in the wild than we were previously. Yeah, so I guess that's.

A: Okay. So you were saying in the future, you might be looking at more evolutionary questions. So, what are future directions?

B: Yeah, so I always get the question, I don't know if I'll ever be able to answer this, but whenever I discuss the project I always get the question "why does this happen?" which I think is a really interesting and great question, but a really really hard one to answer. So what I think is that by looking at other species we can better understand the why

A: Ok

B: Because through comparative biology and looking at these other species we can say, you know, how do they do it. And if all of these species that have one aspect of their biology do it in one way and a bunch of other species do it in another way, maybe that can tell us a bit more about what's the reason

A: Right

B: And so that's part of why I really like the evolutionary biology. I also just think it's, I think it's a cool question. To, it kind of lets you look back at how things used to be. Um, and it's frustrating but it's also kind of interesting to have unanswerable questions (both laugh) um, which is a lot of evolutionary bio. I mean there's a lot of things you can do, you can figure out a lot of things, but you're never going to be able to go back in time and see what was actually going on

A: Right

B: Or study things that are happening over such a long period of time to really test the experiment, but you can get pretty close, and I always think that's really cool. To be able to kind of like, "okay, well maybe a million years ago, it was like this."

A: Uh-huh

B: X y and z was happening. Can I create a worm or a condition that would best mimic x y and z and see how they do. And seeing how they do can kind of tell you more about whether or not that's kind of a positive idea to have.

A: Mhmm. Cool. … um. .. as you were working on this project what new knowledge or skills did you acquire as you were doing it?

B: So I definitely had to learn more computational biology to analyze the RNA-seq and things like that. So I had to learn that, which was really helpful. A little bit more statistics. Could probably still learn more statistics (both laugh). And … skills.. I mean just for this whole postdoc and project in general, I had to learn how to work in C. elegans. I had never worked in C. elegans. I had never worked in a multi cellular organism before.

A: Right, right

B: so I had to learn how to do that. Um, just kind of like the, how to handle the worms and all of those kinds of things. How to perform a lifespan assay. It took a while to figure out whether or not a worm was dead. Which doesn't seem like it'll be that. I mean, like you think about it, it's like of course it'll be easy

to tell when an animal's dead or not. but it's actually, it can be quite challenging. And they die in slightly different ways.

A: Yeah

B: So it took a while to learn that. So I was really reliant on more senior postdocs and graduate students who had been doing it for years to be like "is this worm dead or alive?" and hand it to them, and they'd be like, and then they'd tell me whether it was dead or alive, and I'd be like "okay, thanks." (both laugh). So you know, learning those kinds of things were really critical.

A: Um, oh, yeah, so how did you decide that you were, that you had enough to publish?

B: Yeah. That's always a difficult decision because you can always do more.

A: Right

B: I think a couple of factors. So what helps me make that decision is presenting it, or preparing it in different ways.

A: Uh-huh

B: So presenting it an informal lab meetings, presenting it at formal meetings, and then also writing it up or preparing figures. So that really helps me kind of identify holes. And so the ways it helps me identify holes is whenever you present it to people who have either heard it before or have never hear it put into kind of a story, you can kind of figure out where people get hung up on things or where their big questions are, and that really helps you to kind of take a step back and see how other people view it and what they think are remaining questions or problems. So I always try and pay attention to the questions that I receive, especially if I get them multiple times from different groups.

A: Uh-huh

B: Like, okay, this is a really important thing that I should probably figure out before I submit this. So that really helps. And then just personally when I prepare figures, and in particular when I start writing, or even just writing figure legends and stuff. You write something, and you make this claim,

A: Uh-huh

B: like "this does this", you better have the right experiments to back that up.

A: Right

B: And so by writing it out or by preparing the figures, I can help to identify some of the holes, or kind of think a little bit more about it and make sure that I have everything that I need to have. Or you know sometimes when I just get writing, and I'm like "oh wouldn't it be great if I could say this next" then like I should probably do that experiment because it would be a really great next paragraph to have, to be able to say "oh, and also we found this." So it's helpful for that.

A: Okay. .. Um, and, you've talked through most of my questions, so that's great. Um, if you're thinking about students who you've probably worked with rotation students or graduate students or even undergrads are there particular difficulties that you've seen them have in their problem solving?

B: Yeah, let's see. Okay. Um, part of it is just, um, not having the knowledge or the expertise to know how to, you know, to know maybe what a problem might be. So there is like a certain amount of knowledge base that has to be there to kind of figure out what an issue is. Um, part of it is, and with that kind of, the more and more you've done bench work in this, you kind of develop this proficiency where you can kind of identify issues, or you know a little bit more about where to look to find the issue and you become a little bit more self-reliant, so that kind of helps. I'm trying to think if there's like specific… Um, I think the main thing is that when I'm mentoring is I try to do, is I try to ask questions.

A: Uh-huh

B: And get them to think about the problem with different questions.

A: Okay

B: Um, so let's say we have a particular experiment that isn't working well. Maybe I have an idea why it isn't working, but I try to walk them through all of the different steps that go into. let's say it's just like genotyping or something like that. So some of the ways that we genotype the worms are like you have to pick up the worm, you have to have the right controls. You do a PCR, and then we usually send it off for Sanger sequencing, and sometimes you just have a, like the sequencing doesn't work and you don't know why.

A: Uh-huh

B: So taking them through "okay, what are all the steps that are involved?"

A: Uh-huh

B: So there's the company that does the sequencing, they may have screwed up. There's the PCR itself, there's the worm, um, and whether it's the right worm or the right primers and all that kind of stuff. So teaching them to kind of go through each of those steps and kind of figure out, um, you know. Sometimes just for speed we just do a streamlined version of it. So like if we wanted to figure out like maybe the PCR didn't work, how would you figure out that the PCR didn't work? And they're like, okay, yeah, maybe we should run a gel? Okay, did you save some of your sample, let's run a gel right now, so you know at least what you gave to the sequencing company, it's the right size and you actually have a band.

A: Right

B: So like kind of going through those, I think that's a good skill to learn, to figure out if something goes wrong. Or like, if you have a question, you have that one question, but within that question you can really like expand it out into 10 different small questions, and then going through and figuring out how to um, how to eliminate them or check boxes and stuff.

A: Right

B: Yeah. So I say that goes, not only when you have a problem, but just when you have a research question too.

A: Right. Cool. Is there anything that you'd like to add, or?

B: I can't think of anything

A: Well, this was great

Biology postdoc (2)

A: so what I'd like you to do in this is just kind of talk, um, but basically walk me through one of your projects. Walk me through a problem or a project you have, and particularly focusing on all of the steps that you took. So I want to know all of the decisions you were making along the way and how you solved that problem.

B: Okay. And it can be any of my…?

A: Yep.

B: Many of my problems? Ok

A: Yes. Something science related (laughs)

B: That makes sense. Um. So … um. Okay. Um, so I have in mind, and I hope this is adequate for your research.

A: Yeah

B: Okay. So what I work on - are b chromosomes in drosophila melanogaster. B chromosomes are supernumerary extra chromosomes that typically don't have any essential genetic material on them and b chromosomes can be found in many different organisms across many different taxa. And only recently they were found in drosophila melanogaster. So I am trying to understand in terms of broad, big picture, I'm trying to understand what makes them tick. So what are they comprised of, what are they composed of. How do they segregate during the meiotic divisions and essentially how are they transmitted on to progeny, and etc. So one problem that I faced was trying to understand how these b chromosomes, which I'd determined to not have any genetic material. Or any essential genetic material, or even protein coding genes

A: Ok

B: To be encoded on them. How were they maintained over several generations in this particular fly stock

A: Uh-huh

B: To address this question, I needed to measure the number of b chromosomes that were being transmitted from one parent to their progeny.

A: Uh-huh

B: The limitation on the technology was that in order to determine the number of b chromosomes that were carried by a particular organism, or by a particular um, stock. Was to take larval brain tissue and squash them.

A: Huh

B: So that you can actually physically count the number of chromosomes

A: Oh my gosh

B: Which was totally beautiful, but not. You know. something that I. doesn't work for me if I want to know actually how many b chromosomes were in an adult fly.

A: Uh-huh

B: So what I decided to do was attempt to determine the number of b chromosomes cytological in an adult fly

A: Okay

B: That was the problem. so to start addressing said problem. is this by the way on track to what you're?

A: Yeah, this is perfect

B: Okay. So the first thing I did was ask. Had anyone ever done this before? Um, you know, so that involved a literature search. And with drosophila we've got over a hundred years of literature. So. Right. So what I'd found was that certainly in recent times it had not been done. But some cytology was done way back in 1903.

A; Wow

B: And so I guess, even though that did not give me any sort of protocol or anything to work off of. It was certainly a step in the sense that, it was motivation. Oh okay, maybe this can be done. So the next step I took was to understand why the chromosomes spreads work in larval tissue.

A: Uh-huh

B: And so I spent some time, um. Not much. But uh, understanding the. Like, it essentially came down to the reason why people use larval tissue. Larval brain tissue specifically is because it is one of the most rapidly dividing, most proliferative tissues throughout the fly lifecycle.

A: Ok

B: So there are a lot of cells undergoing mitosis, and in order to see metaphase chromosomes you need cells that are actively dividing. So that is why larval tissue was use. So then taking that knowledge, I applied that to the adult fly, and said "okay, what tissues are really actively dividing in an adult?" It came down to, after a little bit of research, the gut, which is constantly dividing, or at least making new cells, and then the gonad.

A: Ok

B: So in males and females you are constantly making egg and sperm. And there are pre meiotic mitotic divisions in those gonads. So the next step I took was to, um, understand more about the actual larval chromosome spread protocol itself

A: Ok

B: To understand what each of the components did in terms of the fixation, um, lengths of time for various incubations etc. so that I could get a better understanding of how I could get chromosomes in the first place. And then I married those two, you know, inputs, to basically dissect certain tissues and apply different fixation, different methods to see if I couldn't find chromosomes

A: Ok

B: Ultimately the conclusion I found was that the ovary in the adult female, which is undergoing pre-meiotic mitotic divisions, as well as normal mitotic divisions in the somatic cells, the follicle cells that surround each ovarial. Were. I could find enough metaphases to allow me to discern how many b chromosomes that adult female was carrying

A: Ok

B: So putting all that together

A: (laughs)

B: I was then able to take a single adult female, mate her to a male that did not have b chromosomes, then after she had mated and laid eggs, determine the number of b chromosome that she had and then apply the same technique to her daughters. So then I could get a transmission frequency from female – the mom – to females – the daughters. And then determine the transmission frequency of b chromosomes

A: Uh-huh

B: And then what I found was that in this particular stock where the b chromosomes were found, the transmission frequency is greater than the predicted Mendelian frequency. Indicating that they are subject to female meiotic drive. So instead of passing on half of the number b chromosomes, the mother passes on roughly 60-70% of her b chromosomes. So if she had 10, instead of passing on 5, she would pass on 6 to 7 to each of her daughters

A: Huh

B: Which was pretty cool. So. Anyway, and that was. And that's a technique I've been using ever since

A: Ok.

B: Did that, was that something?

A: Yeah, oh yeah. So can you tell me a little bit about what you've been using that technique for since?

B: Sure. So, um. I've been using it for a few things. As I mentioned, it's to assess the number of b chromosomes in an adult fly. And that is my primary use of that. It's also to. I've also been using it to, um. To basically … I have a second b chromosome that we found. It's a little smaller, a little different. But it isn't kept in stock as nicely as this other first b chromosome

A: Ok

B: So what I've also been using this technique for is to basically, um. I don't want to say select, but. You know, if I set up 20 females, 20 crosses, I can then use this technique to see which of them actually carry this second b chromosome variant. And then take only those, that stock. Rather than having. So you know I can try to keep that b chromosome artificially in the population

A: Ok

B: So I can follow it that way. I. let's see. I have also used this technique, and I have shared it with others in the lab, to be able to look at other cytogenetic um, for other cytogenetic purposes. For example, if there are compound chromosomes or chromosome rearrangements, or even just a phenotype we don't understand, sometimes it's the fastest way to just look at the chromosomes and say "ah, this is carrying, you know, a really rearranged chromosome 3. Or this is carrying a y chromosome or whatever that may be." So it's really nice, and this is something that I hope people will continue to use in the future. Is it enables us to directly tie. Or I'm sorry, maybe not directly. But it enables us to take a female that has an odd or unexpected phenotype

A: Uh-huh

B: And then do the chromosome cytogenetic analysis and say "ah, she has a weird phenotype because, she is aneuploid, she has an extra chromosome of this, and she's got. You know. She inherited this weird combination that we didn't expect. Or whatever."

A: Uh-huh

B: So so that's also a use, another use in the lab

A: So what got you interested in the B chromosomes in the first place? How did you get into this project?

B: So, as you know, I was studying DNA replication for my graduate work, and I was examining the effects of re-replication, an additional round of replication through the centromere region in budding yeast. So in general I am interested in how cells control the number of chromosomes they have. And there's a lot of work that was done, that has been done, looking at aneuploidy, or extra chromosomes, and their effect on protein homeostasis, and how they affect the network of the cell. And when I heard about these B chromosomes. Which by the way, the paper documenting the discovery of these b chromosomes came out just a few months before I interviewed here in [Name's] lab

A: Oh wow

B: And so what I was really interested in was the fact that. And I didn't say this earlier, but drosophila melanogaster has 4 chromosomes. So a typical female, you know, a typical fly is diploid, so they carry a total of 8. And, um. 2 sex chromosomes, 2 chromosome 2's, 2 chromosome 3's, and then 2 chromosome 4's, and that's it. But these flies can have anywhere from 10-12 B chromosomes.

A: Wow

B: So this is more than double the number of centromeres that one has, that a cell has to deal with during division. This is essentially. Even though they're very tiny, there are still a lot of like silencing proteins because they are heterochromatic, um, nucleo, you know histones that need to form

nucleosomes, etc. they're still like, they're still chromosomes. And yet it seems like the fly was totally fine.

A: Huh

B: So I was interested in why the cell was allowing these B chromosomes to exist. And again, part of the answer to that was meiotic drive. But also, are there. Like. They really had only been seen at 10-12 copies. And so why are they stalling out at 12? I'm really kind of interested as to why I don't see 20 of them, why I don't see 30 of them, if they don't have any genes on them, right. So it's really more about the fundamental, um, perter. Like essentially the fundamental stress that extra stress can have on a cell

A: Ok

B: And so that's kind of what got me interested in it. And I started. Some of my initial grants, which were not funded, were written about kind of trying to probe those questions. And then I sort of stumbled upon this mitotic drive phenotype, which is also extremely interesting. And um, opened kind of another niche in terms of understanding how chromosomes that don't cross over and are effectively unpaired during female meiosis, how they get segregated. And what dictates their segregation, and how does the spindle move during meiotic segregation, and stuff like that.

A: Huh

B: That is how that's branched. But I still am very interested in why it tops out at about 12. What, what is the stress that these are putting on the cell. Because again they don't have any genes. What is going on? And they are so like. We know that centromeric proteins, kinetochore proteins, microtubules, a lot of those components for cell division are in abundance. So it's probably not a limitation there either. So I'm really just like super excited about that (laughs)

A: Ok (laughs)

B: Did that answer your question?

A: Yeah, yeah. So have you figured out. You know that they're replicating through this meiotic drive. Have you figured out if they do anything, or just they're there?

B: So I, last year, at the end of last year we put out a genetics paper that kind of was the molecular analysis of these B chromosomes. So I was able to isolate them, the whole chromosome on a pulse-field gel, which is a special type of electrophoresis that allows large pieces of chromosome. Or large DNA fragments to be segregated, you know put through the gel. So I was able to actually purify them out, determine their size, cut them out of the gel, and then sequence them.

A: Ok

B: So we, they are. They are rich in transposable elements. Rich in just repetitive sequences

A: Yeah

B: And so, based on my studies and some previous studies from the initial paper. It's. we're pretty certain that these chromosomes are pure heterochromatin. So we didn't find any protein coding genes,

etc. however, all of their sequence can be. Like is drosophila in origin. So it's not like they're some parasitic genome. Or something, yeah. So I also did a bit of FISH analysis on chromosome spreads, to look at repeat sequences, and was able to really nail down that the originated from the left arm of the smallest chromosome, chromosome 4

A: Oh

B: So based on, when we got the sequences back there were some repetitive sequences that I made probes to and determined where the sequence was in the genome, and so on the B chromosomes the sequence was also on chromosome 4. So it really was definitive that that's where they came from. And we think that based on the intensities of that FISH probe as compared to chromosome 4, that what happened was a mis-division, where essentially the two small arms of chromosome 4 broke away from the two larger chromosome arms.

A: Uh-huh

B: And then they just fused. So it's essentially an isochromosome. And the reason why that's exciting is, in humans. Supernumerary chromosomes exist, and a number of them are isochromosome as well. So they are broken from the tip of a chromosome and then just fused.

A: Ok

B: And they can lead to a lot of reproductive problems, so infertility or just a high degree of chromosome mis-segregation during meiosis. And so far there really isn't a viable, a viable system to understand how those supernumerary chromosomes are disrupting meiosis. Which makes these B chromosomes even more exciting from a human health perspective, because… aside from like again some cell lines that were derived from patients, we can maybe start using theses B chromosomes to understand how they're interacting with the essential chromosomes during meiosis to understand how they are disrupting pairing, clustering of the centromeres, assortment on the spindle, etc. and also we can start to understand what causes their formation in the first place. Because we think it was just a random event, but we have no idea. That was just pure conjecture. So what we'd really like to do is understand is it maybe maternal age that contributes to the frequency of these chromosomes? Is it maybe other stressors, you know, heat, or some other. Can we essentially induce this?

B: Uh-huh

B: And so I think that is again something that is, it's in the future in terms of like what I'd like to do when I have my own lab. But it is certainly an avenue that was opened by this molecular analysis

A: Okay, so in getting your assay to work what were the critical decisions that you made?

B: The assay where I'm looking at chromosome from adults? Or?

A: Yeah, yeah, in your initial problem that you described to me.

B: What were some critical decisions that I made? Is that what you asked?

A: Yeah

A: Uh, let me think. … Well, if I'm goanna be honest, one of the things that one of the things that I ran into a lot was why are you doing this?

A: Okay

B: Like, this is not going to be like, this isn't going to work. (both laugh). And so I guess a critical decision I had to make was.. do I listen to people who have been in the lab, not that they've necessarily tried the protocol I was attempting to make, but, um. Do I listen to them, they've been in the fly field longer, they've been in the lab longer. And these were people who were staff scientists. So you know, they've got some, they've definitely got some clout. Or do I say no, I think I'm in the right direction. I think I'm moving the right direction. I think I'm seeing, I'm making progress, do I continue. So a critical decision was to continue.

A: Uh-huh

B: You know what I mean? Which I know was not a, yeah, it's not like a scientific you know decision, but um, but it was certainly an important one

A: Uh-huh

B: Because I think it's easy to talk oneself out of an experiment. And sometimes you have to listen to what people are saying because you can go down a rabbit hole and come up with nothing, but, um. Would you like more scientific decisions?

A: Um, yeah, maybe but actually before that you said "I could tell that I was making progress." Could you elaborate a little more on what was happening there?

B: Sure. So I was taking a protocol that I had for larval brains that I knew had worked, and applying that to various different tissues. So iw as applying that to gut tissue and then to gonad tissue from both males and females. And so I was making progress because, I felt that I was able to see. It wasn't just a mess on the slide. I wasn't seeing any mitoses

A: Ok

B: But I was seeing, I was seeing nuclei, I was, I was able to see that I was fixing the tissue properly, because of how it looked. It wasn't just like completely decimated. It was intact. I was also confident that I was looking in the right. So I was confident I was looking in the right place for various tissues. So it was just a matter of refining. So for example with the females, the pre-meiotic, mitotic divisions are in the very tip of the ovary

A: Ok

B: So I felt that maybe I was putting too much of the later tissue on the slide. Because kind of there was just so much tissue. So I said ok, I know my fixation etc seems to be working by the qualitative assessment of inte… etc. but I think I'm not getting. One component for these squashes is the squash itself. I think I'm getting too much material, so it's not allowing me to really squish as hard as I need to, so I refined how much I was taking.

A: Uh-huh

B: So. I. so a little less than I was initially putting on. And it made a big difference. So it allowed me to really squish and really squeeze to a very thin thin thin layer, which allowed the chromosomes to splay more and I could see them better. And so once I saw one (both laugh), once I see one mitosis, I say "ah-hah, okay, chromosomes look good, so let's move on and try to increase the number I can see"

A: Uh-huh

B: So to do that, it's more fine movements to kind of. So the tissue is really bunched up at the tip of the ovary, so I tried to kind of untangle it a bit before I squashed, and that helped. So there were just kind of fine adjustments after that, but yea

A: Right. Okay.

B: Does that answer your question?

A: Yeah.

B: It's kind of a boring assay when I talk about it, but it took a lot of work

A: (laughs). Yeah, so are there other, you were starting to think about if there were any other critical decisions that you made.

B: For this particular protocol?

A: Yeah, or if there's something else where you're like "well, there's this other thing!" you're welcome to branch off if you'd like.

B: Uh, well I think kind of building off of that. Once I was able to get metaphase chromosomes reliably from the tissue, I was then. I then tried to do immunohistochemistry on it. Whatever it is where you use it for microscopy. I think it's immunohistoflurescence.

A: Ok

B: Whatever. Um, I was trying to do immunofluorescence on these spreads, and um, and that kind of took a lot of, again that was kind of incremental where the fixation that gave. And this is a problem again going back to the literature. You know, for people who look at nucleic acid vs. protein in other tissues like the embryo for example, the fixative is very important because it preserves some structures but not others. So if you want to look at DNA there are some fixatives that are better for that. If you want to look at proteins there are other fixatives to look at that, and it's really a balance between the two.

A: Uh-huh

B: If you want to look at both, which is what I was then venturing to do. So I essentially started to manipulate the protocol to enrich for, enrich for highly condensed metaphase chromosomes. So I applied a drug that then would essentially arrest cells in mitosis. So then they would get really condensed and tight, which actually helped with keeping their temperature through a fixation and the heat. And Uh, let's see. So then little things like that, trying to play around with. Like one thing or

example, I was trying to look at the centromeres and the centromeric histone on these chromosomes to see if the B chromosomes had it, which we knew they did but I was trying to verify it

A: Uh-huh

B: And that was a hard time because the fixative I was using contained acetic acid, and acetic acid actually strips DNA of histones,

A: Oh no

B: so if you want to look at centromeric histones you can't use acetic acid. And so I was trying new fixatives, and basically doing a fixation and then immediately looking to try to see the DNA and then if the DNA looked good, then go back and then. So it was essentially almost a table. Right. Of, you know "trial 1. Fixative: what was the fixative, it was this? How long did you do it for? This. Did you add this? Yes or no."

A: right

B: And then modifying things. And then you know "result: looks like I didn't fix long enough." Okay, change the fixing time. You know, and then so just going through until I could actually get something that looked right.

A: Uh-huh

B: Which I did!

A: Great

B: But I hope I never have to do that again. That was a pain. But anyway. Yeah.

A: Okay, um. And, let's see. You already answered that. Oh, okay. So how did you decide that you had a good enough solution?

B: How did I decide that. Oh, let's see. … (sigh). I decided I had a good enough solution when it was easily reproducible.

A: Ok

B: And I think that one can try try try try again, get something to work once and then be done with it. And I don't. I you know. whether that's the training I received as a graduate student, or what. I think that it's actually. I was satisfied when I could reliably get what I needed. So for example, with the chromosome spreads from a different tissue. I could have stopped when I saw that one mitosis, or at least "oh this is sufficient, this is good enough." But the problem was it wasn't reliable. I wasn't able to get enough mitoses every time. So I concluded my troubleshooting when I could reliably. That means at least 9 times out of 10, I can do it 10 times out of 10. … Um, spreads and be able to count number of metaphase chromosomes that I need to count. And yeah, feel like I could do that every day. So that's where I stopped with that. And I always think about the thing that I. [Name] actually said it. "if you do an experiment and you get the result you want once, it's probably not right. If you do it again, and you get the result again, then okay, you're on to something. And if you do it a third time and you get what you

want the you're golden." And that's kind of like how I felt like when I was like able to do it. And then also teach it to somebody else and actually have them you know reproduce it and get the same results, that was extremely gratifying, so yea.

A: Okay. Um, and. So where, like. I guess where did this go? Is there a paper on this? Is it part of a bigger project, where did it end up?

B: So this protocol was mentioned, um, well used, and. This protocol was used in that paper that was. Its' in [Journal] in [Month].

A: Ok

B: And it was primarily used, um. Uh, it was one experiment in there. And now I'm blanking on which one it was. But anyway, that's okay. Oh, I know what it was. It was to assess the number, it was to assess the frequency of this second b chromosome variant in the population.

A: Ok

B: So basically if you took a swath of females from the population, and then said ok, how many of them have this second b chromosome, how many don't? And so we were able to directly assess that. Rather than to take larvae which could all have been laid by a single female. Or you know, not a representation of the whole population. This was just a good way to do that. I really really really want to do a [methods journal] article on this, because I was asked to do a Jove article, but I think that that is not in the cards right now. [Name's] like, we had a number of papers come out last year, and so [Name's] like, kind of. I think he's being a little more selective with papers. Because they are. They're kind of costly. (laughs)

A: Ok

B: So um, but I would really. I would love to do a protocol for this and publish that. Because I think it would be valuable for the drosophila community. And also on top of that, just to extend that. Part of the problem in general with b chromosome work is. Or even a lot of drosophila work, it doesn't even have to be b chromosome work. Is understanding their cytology.

A: Uh-huh

B: And a lot of times for drosophila, because of the established protocols for doing chromosome spreads in the larvae, they. If you can't get a fly species that you collected from some mountain top in Utah to actually reproduce in the lab. And make larvae for you, then you aren't. you can't do that cytology

A: Interesting

B: Whereas this protocol allows you to take adults from the wild and directly assess their chromosome content.

A: Right

B: And I think that that will have implications for more cytological studies, like kind of evolutionary cytological studies

A: Uh-huh

B: For again more field biologists. But anyway, that's like a far off dream

A: Sure

B: But the other thing is this protocol is absolutely used. Or will be used in the meiotic drive paper that I'm currently trying to get out. So that is kind of the bread and butter assay of again taking a single female and measuring her, the transmission frequency from her to her progeny. Rather than doing a population based study where you take a bunch of females and take all the larvae and don't have a good sense of who came from what

A: Right

B: Another too is if you found, this has not happen to me, I should make sure I specify that, but you can't say it can't. If I was to take females and do chromosome squashes on their progeny as larvae instead of as adults. If I found the larvae with say 20 b chromosomes, right? Will that larvae have ever become a breeding adult?

A: Ahh

B: And I think that's something that in terms of if you want to think about transmission of this b chromosome in a population. If for some reason it gets, you know, this one particular, you know organism got a whole bunch, it may be dying during pupation. Or it may actually not become a breeding adult in the population

A: Right

B: And so kind of taking a female and then taking her adult breeding progeny. I think solidifies, you know, the argument that these are being transmitted in a preferential way. To. And they are being. They are in breeding adults. Anyway, so that is an important assay.

A: Okay. Um, can you tell me a little bit more about what else is going into your meiotic drive paper?

B: So as cool as it is, transmission frequencies are just graphs. So it's like "yay, transmission frequency from females to her progeny, and from males, you know." and so kind of to make it more interesting as well as more biologically compelling is cytology. So one thing we are working on now is trying to. Well, it's kind of two pathways. Um. One is fixed imaging of female meiosis

A: Mm

B: And the way female meiosis works, the divisions, the actual divisions during meiosis. The females are constantly making eggs. As the egg passes through the oviduct, it simultaneously gets fertilized and activated, and it's that activation that triggers the meiotic divisions. Often when that egg is laid, the divisions are either in progress or already done. It happens extremely quickly.

A: Wow

B: So what needs to happen is either you need to catch those eggs very early, so you need to catch them as they're coming out of her. Or you try to, you try to. Well, one technique is to squeeze them out

A: Okay

B: Which someone, a research, a visiting research technician in the lab is trying to do. I'm not entirely convinced it's going to work, but that's okay. It's something to try. I'm open to options at this point.

A: Uh-huh

B: And um, but the other. And so but basically you'd collect those eggs, you would fix them immediately, and you then would look at where the meiotic spindle is. You would look to see where the b chromosomes are using a FISH probe, and try to understand are they mis-segregating the first division? Are they mis-segregating in the second division? Are they even on the spindle? Maybe they get kicked off and get acquired during the, uh, essentially what happens is the sperm brings in centrioles and they nucleate microtubules out to grab the meiotic product. Maybe they're grabbing b chromosomes. Who knows. You know, I have no idea.

A: Huh

B: So the other option is to activate fly. To activate these eggs in vitro.

A: Ok

B: You can do that. And I have had some success in this. Where you basically dissect eggs that are later in development, like they're. they're being held by the female, she's essentially just waiting for prince charming to come along.

A: (laughs)

B: You dissect them out and you put them. You dissect them in the absence of calcium. Be gentle because pressure can also activate the eggs, so you. Careful. And then you can put them into a chamber and then if you have a fluorescent protein that labels the spindle, like you know, tubulin GFP. You can find the meiotic spindle. And then add in essentially a boat ton of calcium chloride

A: Ok

B: And that will, that will activate the eggs. So then you can watch the meiotic divisions live. The problem with those. So I suspect what it may come down to is a combination of the in vitro activation and the fixation so we can get a better idea of where everything is. But we're still in the process of trying to figure that out. In terms of what is the best way to do it. So that cytology will hopefully shed a little bit of mechanistic understanding of okay, they're transmitted preferentially, but how?

A: Right

B: And what is, you know. Rather than trying to get at more genetic, like what are the players involved and how are they regulating this, that, or the other thing. It's more like, okay we know the b's are being transmitted preferentially. Where are they? Is it in that first division, second division, etc? So that's what's going into the meiotic drive paper. So far.

A: (laughs) Okay, so we've gone through most of the questions I have. But kind of thinking a bit more about research process, and like. If you were back in your graduate school days, how do you think you would have approached this any differently?

B: Uhh, that's a good question. Um, like later in my grad school days, or earlier, or both?

A: Either one, just kind of thinking about you as less experienced than you are now. What has the experience gained you?

B: … Shoot. What has the experience. Um. I think maybe. I would like to think. I would like to think that I do a better job doing a little more research. In the sense that, um, like I think that I do a better job, or have more experience finding or seeking out literature pertaining to something I'm seeing, or a technique, etc. and trying. And then, also unfortunately it's just experience, trying to then say "okay, this has been done before, or this hasn't been done before, or is this an important thing?" you know what I'm trying to say?

A: Yeah

B: So I think like if I think back to my graduate school days, when I was trying to work through some of the problems that I had in that lab. It was, I want to say like, there may be some red herrings that if I maybe had been a little more experienced, or had kind of thought more about. And this actually is another I think important thing. If I had thought more about the story, as to the direction of the research. Like, you know, I maybe pursued things that were interesting but not, they would go nowhere. You know what I mean?

A: Uh-huh

B: So I think being able to more efficiently find things in the previous. In the established literature pertaining to a technique or to what is known about some biological process. And then also combined with okay, what is the story I'm trying to tell. Um, you know, making note of this interesting observation, but also saying okay, I'll keep that over here for this little vignette, but I need to focus right now on getting this technique to work because this is what's going on. You know. So again like the cytology, I have a million other interesting cool ideas, things I want to follow up on, but if I want to get this paper out, I need to focus on the cytology, getting that working

A: Uh-huh

B: Getting that established so that I can finish with that so I think that takes. That's also something that I'm learning. I think that that's probably one of the hardest things for me. But, yeah.

A: Okay, and are there particular difficulties you may have noticed in other, I don't know if you have grad students and undergrads there or not? So are there things you've noticed in less experienced students that you're interacting with? Challenges that they have?

B: Yeah, yeah. So briefly the [place] has a graduate program.

A: Ok

B: It's in it's [number] year? I can't remember. We have a recruitment party this weekend. So whatever year that will be. It is, it is a candidate for accreditation. Meaning it will be officially accredited sometime in the near future. And my boss is [position] (both laugh) yay. So I k now a lot about it. And yes, we do have graduate students here. There's also some other programs that have graduate students that come through here. We also have, um, young investigators. Like undergraduates who are from the neighboring [place].

A: Ok

B: And also summer scholars who are undergraduates doing summer programs. So when they come in, one of the things that I notice is. And again, I think this is the [Name] in the back of my head. Is the, uh. I'll ask them "well why are you using this reagent?"

A: Uh-huh

B: What is, what is the difference between this reagent and this reagent, you know? I actually, this was a conversation I had with a research technician who has been in the lab for about a year now and she's been working with me. And I've been trying to drill this kind of stuff into hear head, because I think it's very beneficial in the long run to have these skills. And there was something recently that she said to me, and it was well this particular technique or whatever has never been done before. And I said "false."

A: Huh

B: So I pulled up a paper and I showed her, you know, and then I pulled up one of my own movies and I showed her. This actually has been done before. So I'm continually like, if you don't know, just look it up. So I try to force her to get better at using resources like PubMed, or just google, or knowing where to find the protocols online to understand. Again, why we use this reagent, how does this work? If I see this under the microscope, what does that mean, you know? for example, in these squashes, you need the pressure to be perpendicular to the slide

A: Ok

B: Because otherwise, if you slide parallel, you can shear things. And then it's crap, right

A: Right

B: So if your nuclei that are intact you know that are in the middle of G1 or something. If those intact nuclei are not nice and round, they're more slanted or look like they've been sheared. That's an indicator.

A: Right

B: So I've been trying to tell her, or trying to encourage her to look at the literature, to understand, you know, what telltale signs in a prep or whatever it is that she's working with, how does that inform you on what to change in the protocol.

A: Uh-huh

B: And I think she's slowly coming around to it. And it's always the most gratifying thing when she's like "well, this paper said." And I'm like "show me the paper." And then I'll be like "good call"

(both laugh)

B: And so I think that that's. I feel like that's the thing that they just. I just. The young ones (the young ones!).

A: (laugh)

B: They just don't know. it's just weird. They don't realize they can, in a way. You know what I mean, it's like they don't. when I ask them a question, then I'm like, how would you figure that out?

A: Ah

B: Like, I have no idea. And I'm like, let me show you how to figure that out. And then it kinda blows their mind, they're like "whoa". So I think that that's. once they start really putting that into practice they get. I mean it's just, all down hill from there, they're on a roll.

A: So practicing figuring something out?

B: Yes, so that is really. To me that is the crux of it. It is. It is, and I kind of think about that when I think about like, you know raising kids or whatever. All those questions like "why does this happen?" "why does this happen?" you know, kind of the old joke. And I'm like,. the thing I want to be able to say to my kids, whatever, will be "how are we going to figure this out?"

A: Yeah.

B: Like, where do we need to go, where do we need to look? You know, can we just google it? Is it something we can just search online? Is there a particular reference that's better suited for this? I think that practicing that, especially in the lab. You know, google sometimes is great, but it can take a while to get to what you actually want.

A: Right

B: And so, knowing what's out there. Like when I can. When I show them current protocols online, you know. like I think some of these kids are like "oh my god. It has all the instructions and why we do it like this and illustrations!" and I'm like "yeah, you are not the first one to struggle!"

(both laugh)

B: So yeah practicing that I think is really important

A: Ok

B: At least through our lab, I have not seen anyone who is. Who is unintelligent.

A: Yeah

B: Like, I think everybody comes in kind of with some sense of curiosity. And just helping them look. You know find what they need to find and where to find it. Like I think that that just opens so many doors.

A: Yeah. Great. One final question, since we're almost at an hour um. So something that's come up a lot with other interviews we've done has been people's use of models. So I was just wondering if in any of yoru stuff you have models that…

B: I tend to like models as well.

A: (laughs)

B: But I also like models because I'm lazy. So with papers. Actually, [Name] just had a paper out in [Journal]. I was just looking at the table of contents, and I was like, "oh cool, okay what did they put out?" Not that I'm particularly interested in what his lab does. But just wanted to see what they did. And so I click on the paper. So a bunch of beautiful scientific data, and I'm just like scroll, scroll, scroll down to the model. Because it kinda puts it all together. Especially for things where I just want to have some idea of what's going on

A: Uh-huh

B: If I want to be like, well you know, I saw a paper recently that looks at Ire1. So I do like models. I'm a visual learner for sure. And there's a model in my paper about how we think the b chromosomes were formed.

A: Uh-huh

B: Models can be very dangerous though. Because it is meant to be a simplification of a bunch of hard work. And sometime if one is not careful, it can be, either an oversimplification or an overstatement.

A: Uh-huh

B: Of what the data says. So I like models, but I also am like, always wary of them.

A: Mhmm

B: Um, and sometimes they can be helpful too when you're trying to figure out a process or something to be like, oh if I want to draw a model of this what steps do we know, what steps do we not know. But um. Is that?

A: Yeah, that's great. In the project that you were talking about this whole time. Um, did you, other than the model that you created at the end, were you using models along the way at all?

B: … Um. Not really. Which is odd.

A: (laughs)

B: You know. I mean, I think. Yeah. To be honest, like in the. In a weird way because what I'm doing is so, uh, like there's so much we don't know. it's kind of hard. In some respects it's kind of hard to make a

model, because you're just like "they're transmitted preferentially. I have no idea what's going on." We have some clues as to what's contributing to that, but otherwise it's like "we don't know" (laughs)

A: Right

B: So right now it's a little harder to make models, at least for the meiotic drive stuff. For the b chromosome formation, that was also a very simplistic model because it was like "these are the repeats. We've measured them. This is probably how it was formed." But aside from really simple things at this time, um. Cause we just don't. you know, there's just not a whole lot of. Um. I think, I think the models I have right now are more of a collation of data, than it a like "this is how we think this works."

A: Okay. Well, great. Thank you very much this was super helpful!

Physics (theoretical)/Chemical Engineering faculty

[Interviewer]: Okay. Um, so we're interviewing you as part of a project to identify how experts think as they solve problems during their research. And our goal is to, ultimately, identify what students ought to be learning to do, in order to, uh, improve education and improve how students solve problems. Um, so, today we want to know…uh, we want to learn about how you solve problems by having you think about a problem that you've solved recently—or a recent project that you've worked on—and walk us through all the detailed steps. Um, with particular emphasis on all of the decisions that you made as you went through and solved the problem. Um, yeah.

Expert: It's a big, tall challenge for that one. So, I thought about this and, so I thought about, uh, something I could tell you about. A story about some work that I did….Can you hear me okay?

[Interviewer]: Yes.

Expert: Okay, so work that I did, actually, uh, when I started working, uh, on microrheology. Something [Interviewer] knows something about, so he can provide background information if you have anything…in the future you may need. And that was when I first started this with a student—a post doc actually—[Name], who was a postdoc at [Institution 1] in the physics department. And, um, [Name] actually wasn't working with me, he was working with someone else, but he had a fellowship which allowed him to do what he wanted to do, and so, he would come over. And he was taking a class I was teaching on, just, special topics in transport processes, and in that class we required everyone to do a project. And, so, [Name] then decided to do a project and so we thought about some particular problem, we started talking about it. And, um, so we just sort of discussed this, we had some ideas about how to do this particular, uh, problem we were thinking about. Um, and then in the course of thinking more about that, um, we thought that there would be a simpler way to do this. And maybe we shouldn't try to do the problem we actually set out to do, but to do something which was closely related to it, but something perhaps a little more simple, that we could then make progress on. And that's a theme I would like you to…to emphasize that I do a lot in my work, is: have a goal, want to solve a particular thing, but that turns out to be too complicated, or we don't know enough yet about how to do that, and so we try to back step a little bit and try to find something which is simpler, that has features in common with the problem we want to ultimately solve, but that we think we can actually make some headway on. And hope that we'll learn something in the process of doing that which would eventually get us back to being able to solve the problem that we really initially posed. And I do—try to do—that a lot in the research I do, is to address problems in that kind of way: find something which I hope is a simpler approach and sometimes…sometimes it turns out that the simpler approach turns out to be the better way to go, and that's all we ever do. So, in the context of this microrheology problem, um, that's how we talked about it. You know, [Name] and I would meet, you know, once or twice a week and just discuss through ideas on the board—talked about things—and then, finally, we distilled it down into this, sort of, simpler problem of just: what happens if you move a particle through a complex medium—what are the forces acting on it and so on? And that, then, led to a whole area of research, uh, not only for me but for [Name], and other people, and they actually wrote a book on this topic now. So it really led to a lot of different things, uh…

[Interviewer 3]: Can, can I interrupt for just second? Can…

Expert: Sure.

[Interviewer 3]: Can you, can you give just a—not an enormous amount—but just a little bit more of the details between: what was the original problem you were discussing and then how it worked to this whole new field that ended up a book?

Expert: Uh, so the original problem was, um, there have been observations, um, in flows of particles in…in fluids, that is if they're under shear flow, at a high enough concentration of particles, you can get migration of particles from one place to another place through interactions amongst the suspended particles. And so, uh, [Name] thought that was a nice thing and maybe we could think about how to look at that from a different point of view than people had thought about previously. And, um, so we started thinking about that but that's uh…that's a complicated problem. It involves, um, many particles interacting with each other and it's just a larger more difficult thing to think about. Uh, so that was what we initially talked about, um, had some ideas, you know, and had…maybe we had, you know, three or four different, uh, thoughts or approaches we might try, to…how you might try to, uh, solve that, address that many-body interaction problem…to make headway. We had, you know, try this approximation, maybe we can model it this way, um, and…and sort of we're approaching this from all different kinds of angles and different kinds of perspectives to try and get some insight. But, you know, in some sense, have an idea to get a hold of the problem to be able to really make headway. And so we must have tried three or four—at least—different approaches. We would work on it for, um, you know a week or two, think about it talk about it, uh try to make things, try to make headway, and um that's sort of how we worked our way around to this other approach that turned about to be much more…easy…and, and actually more insightful to what goes on, so…does that help [Interviewer 3]?

[Interviewer 3]: Uh, it does, but now can you give me a quick summary of the other approach that you arrived at?

Expert: Okay, so the quick summary of what we arrived at was simply that we distilled it down to the simplest possible case, which is just if you have a single particle and you grab hold of it with an external force and you drag it through this complicated medium, then we could figure out what the relationship between the force and the velocity was, which then, uh, is a way to…what's called microrheology basically, is how people measure, from a microscopic perspective, the rheological behavior of a complex fluid. You just watch the particle move around. And it turns out you can do that, um, experimentally by w…just watching the Brownian motion of particles. You can just watch them and from their motion you can correlate what some kind of material response in the medium is going to be. So it opened up a whole new perspective on how to do those things, and, and, and simultaneously people were starting to do that experimentally. Because you can now synthesize particles, you can observe them under the microscope, it became much easier to track them. People had developed software to track the particles and so, at the same time, we developed this sort of theoretical approach to these things. Uh, and in particular extended out of the sort of thermal fluctuation limit to nonequilibrium processes from our perspective, and that's what gave rise to a…to a different area that's called microrheology now. So people's views accumulate…

[Interviewer 3]: Okay, thanks. Thank you.

Expert: Questions?

[Interviewer 3]: No.

[Interviewer 2]: Uh, so actually I want to interrupt before [Interviewer] starts asking. So, when you were saying, before you got to the…the…your final…um, your final more simplified problem.

Expert: Approach.

[Interviewer 2]: Yeah, your final approach. You were saying you were trying to make headway. Can you go into a little bit of detail about…about, you know, what you mean by headway and, and what that looked like.

Expert: So it would be, um, you know we would try an approach. We'd say let's try to look at it from this point of view, this perspective, and what…for that…for us, since we're doing some theory, would constitute require writing down some equations, some models. You know, in many cases it's easy to write down the full problem with all its complexity in it, but then you just can't make any progress, and so you have to try to think about, um, some approximations. And, so, that really translates into what do we think is the basic, uh, physics which is governing this particular process we're interested in modeling, and then how do we translate that into some sort of, uh, simplified mathematical description, which we can hope to sort of interrogate and understand. And, so, we tried some other perspectives, uh, more of a…in this context it would be more—[Interviewer] can try to fill you in better—more of a continuum kind of perspective where we wrote some constitutive….kind of continuum, macroscopic equations for describing the concentrated suspension flows, but to...solve those are challenging. And we were approaching a different kind of thing and had some ideas about what they involved, they involved some long-range hydrodynamic interactions which are complicated and, just, uh, unnecessary it turns out. Uh, so we explored a lot of different avenues to try to get things down, so, um, and that involved, you know we'd….we'd have an idea, we'd write down sort of a—more or less detailed—mathematical description, and we'd then spend a week or two trying to solve it to see what it would tell us about the behavior. See if it made any sense, um, you know, can you solve it? And if you could, what kind of results would it predict. And, you know you can estimate things and, and you predict something that makes no sense, and so you say well that's obviously wrong. We need to just back up and so on, and that's how it happens often…we make a prediction or solve a model and then, you know you scratch your head and try to understand does that result make sense or not by some other physical…simple physical thought process, does that make sense or is that too large, too small, or…check this limit out. Does that go to make sense that if I reduce it to…and you know oftentimes you discover, if I take a limit where you know what the answer's supposed to look like and this thing doesn't produce that answer, then you know you're on the wrong track. So that's how we would often eliminate those approaches to try and solve those problems.

[Interviewer 2]: Thanks.

Expert: That help?

[Interviewer 2]: Yeah.

Expert: Okay. Good, good.

[Interviewer]: Um, so, my question was: how did you ultimately settle on this microrheology problem in the first place—that you wanted to explore this area?

Expert: Okay, so that, unfortunately will maybe…unfortunately for you…by chance, by happenstance. It was not something—I'm sorry about that—it was not something that we really intended to do, it really arose out of this class that I was teaching, that everyone had to do a project. And, so, uh, [Name] thought he would, this would be an interesting kind of project to look at. It wasn't microrheology at the time, it was a different…different question, but um that's what it ultimately led to. So, I…I can't tell you

it's something we had a great design that we would do this. And, we saw this as a particular area in need of study and so on, it wasn't that way, it evolved much more organically just by, uh, exploring different ideas and it led to this thing, so.

[Interviewer]: Do you remember what his original question was, or?

Expert: No, it was just really just the context of this class to try to, um, do a project, he had to do something, um, and he was thinking about the migration phenomenon in concentrated suspensions, and trying to look at that problem from a slightly different perspective, people had um, people had done some experiments, as you know, um, and there were some simulations of it and there were some simple calculations, but he wanted to look at that from a different kind of perspective. Um, and that's how we…started on this…on this path, so…right, it led directly into microrheology, but it was really distinct from it and not our intention, so.

[Interviewer]: Right, okay. Any question from the…

[Interviewer 3]: I think, just continue.

[Interviewer]: Yeah, so you can continue where, where you left off in your story. Which was, I believe…I don't remember now. Um, but…

Expert: So, I don't know what more there is to say to the story in some sense. So we basically then took this approach and that opened up a whole new way to look at a whole class of these kinds of problems, which um, uh [Name], when he left here he went and got a faculty position at [Institution 2] in chemical engineering, um, and um continued on this as part of his research. I had a student who worked with me right after [Name]—[Name]—who then went to work with [Name] as a postdoc, so it helped [Name] get started in his academic career, having good a problem area which there was a lot more things you can do, and interesting things to do which were impactful in terms of people doing experiments. So I think it was helpful and beneficial to him in that way. And, then I had other students, uh, work on it, and actually [Interviewer] has worked on a variation of this thing now with regard to active matter. So it sort of, still…still on going. Um, um and then [Name], um, when he went to [Institution 2], hooked up with a professor named [Name] from the [Institution 3] who was doing experiments on these kind of systems. So they really got together and decided that the area was mature enough and important enough that they should write a book so people can, uh, understand how to do these things, how to interpret their measurements and so on. And so they have a book on Microrheology now, so.

[Interviewer 3]: So, I…I guess what, yeah, the thing might be here is, you know, you've talked about the evolution of, of thinking about this and coming out with oh, here's a simplified, you know, or a, a simpler system you decided you can make progress in, and so then you worked on that system. And so, and then presumably produced a bunch of results, those made, you know, those were important and you could understand them. So if you could talk us through that whole, that whole process really, of, I mean in, the, you know from the…from the deciding on here's a simpler worthwhile problem, to, to you know…

Expert: Mhm. So you want to know more in detail what transpired after that in some sense?

[Interviewer 3]: Yes, yes, exactly. Yeah.

Expert: Okay, so….so…the

[Interviewer 3]: Down to the…down to the point of, here's papers we've published on this, okay.

Expert: Right. So then basically we um, so, working with [Name] we sort of narrowed it down to this approach that we could take that seemed like a reasonable approach. And then that involved, um, basically writing down the simplest possible model description we could have, that we were then able to try to solve and we could solve it in, uh, sort of, uh, what would be called a near-equilibrium linear-response kind of behavior where we knew it connected back to some answers which were known. And so we knew that this way we were thinking about the problem would reduce down to something which people had done in different kinds of ways, and so we knew that was a good foundation to go from, that it was, at least worked in that limit. Um, then we could think about, um, the, as we varied a parameter which is important in this case—the strength of how fast you, uh, move a particle—how we could then…describe it completely in the entire regime range, and get ourselves up to the other limit of very high external forces in this sort of context. At the same time, um, we then also could think about, okay that was a very simple model that we made, um, and we've made a lot of assumptions, approximations. Um, let's go back and sort of write down the more complete description of the problem, and then sort of systematically show where this simple model would come from. How did you reduce it down from the more complex problem. And that's another thing which I think is perhaps relevant for what you're thinking about in this context, and that is, you make up some mode, um l and you…now, now, now hopefully you've found something which makes sense and things are working well and you've made a lot of guesses, assumptions, you know, Ansatz they would say in the old day. You know, just jump in there and hope it's doing well, and then oftentimes we'd go back to sort of try to formulate the problem more thoroughly, more systematically, more completely, to understand better exactly what were the approximations that we made—did you have to make that assumption or not?—maybe you didn't. Now you see it more clearly, you see it more broadly, um, and so sometimes you can make it more general than you might have thought because you see that, oh, I didn't really need to make that assumption. It's okay, and that makes it more applicable, and so we did that as well, went back up and wrote down the full problem, so to speak, and then saw how the approximate problem fitted into that description. Um, we also, in this context, then, so now we had a description to measure, uh, the, if you will, the rheological response from a microscopic perspective. Um, I had also done, as a lot of people had, a lot of work on macroscopic rheology—that is, deforming the material overall, not from pushing a bunch of particles through it. And, so we could try to make a connection, comparison from what's known to other ways that you could investigate the behavior of the material. And that also, uh, gave us some insight, and we could understand how it was similar and how it was different, and what the connection was, and so then how you could interpret the one measurement compared to the different measurement and understand what's going on.

[Interviewer 3]: Now, in this process, um, I…you know, when you're talking about examining the approximations and assumptions and so on, um, I want to make sure that I'm…I'm going to put words in your mouth, but I want to make sure they're the right words. I'm assuming this was much like what you were talking about before, where you would then think about how to represent that mathematically, you would then how to…try to solve the equations and see what they would predict and iterate that same way—or was there differences at this stage?

Expert: I think it's pretty much the same way. Um, it would always be try to, uh, to solve the equations, and you know, solve them can mean many different things, because you know on the one…I think most of this work…I think that almost…almost all of it was done analytically, sometimes that's not the case. So, this case we would solve things and work things out and get an answer, and then we might go back and, and try to solve it a different way to make sure the answers agreed with each other. So, oftentimes

we would do that kind of iterative process as well where we'd solve it one way, and then we'd go back and try to solve it a different way. So maybe the same equation or maybe two steps earlier in the starting point and trying to approach it from a different path, um, even still mathematically a different path, just to see if they agree with each other to give us better insights. And, uh, all throughout the time, you know, we're thinking in our heads in some sense, about does this make sense. You know, we always ask ourselves questions. Okay, well if I change this, does that result still make sense or not, or do I find something that's a physical and so on. So there's always, always, you always had that process going on all the time, of, of asking questions about, you know, trying not to get too excited about your answer in some respects, but keep asking does it always make sense. And if I change these conditions or I do something a little different, does…is it robust, and still keep describing things correctly, or does it fall apart? Because that's another way to see whether your theoretical ideas are making sense or not. So.

[Interviewer]: Okay. Um, so, something I was wondering about, and I maybe I'm just not…remembering, but, um, were there any instances when you needed to sort of go and seek out new knowledge or skills to…solve this particular problem?

Expert: Um, I'm, I'm thinking, sorry for sitting and pausing for a moment. Um, in this particular case I don't think so, in the sense of, it wasn't like we had to, uh, had to, had to invent any new mathematics or anything like that at all. I think we had the, I think we had the skills and the pieces of information in different places, it was more a matter of bringing them together from different areas to, to work in this particular, uh, thing. Um, some work that we did subsequently, that people then developed some simulation capability for this stuff, that required a little required a little bit of rethinking how to do those things, but not really learning new skills, uh, necessarily for that. Uh, we also had to solve some problems num[Interviewer]ally which involved, in a different way some, some finite element calculation kind of things. So, people had to go and develop those skills, but there were not, um, you know, super new things that had to be developed. Or it was something we had a base to go from, may take you several weeks to get up to speed how to do it properly, but it wasn't something that was really a super challenge in that sense.

[Interviewer]: Okay. Um…

[Interviewer 2]: The question I always ask is, uh, what were the…critical decisions that you made as you were solving, um, I guess the, you know, a discrete aspect of the problem?

Expert: Um, critical decisions. So, um, I think the, the most critical decisions, as I try to state it, is to back up to something that looks simpler.

[Interviewer 2]: Mhm.

Expert: Um, that, I think, is the real, critical point because you can often spend a lot of time struggling with something, and it's just too difficult. You don't, you don't have the physical insight to make some headway, and so the critical decision is to sort of put that aside a little bit and try to, uh, get something which is related to it, but close enough. And, and something that you can actually make headway on. I think that's a critical decision point that I've used often and seems to be fruitful. Um, while working on something, um, I think the other…I don't think it's necessarily critical, but it's critical in a certain way…is to, um, make sure that you have checks, al…independent checks along the way. Because if you're going off into some new thing which people haven't done before, you know, how do you know you're right? And so you have to really, uh, make sure that you examine things from all different kinds of perspectives. Uh, to, to be, to have confidence that it's working out and things are going the right way.

I'm trying to think of any other critical steps on the way. Um, we also did, you know, uh, draw pictures and graphs and compare to experimental results and computational results. Um, those are important, um, some people might consider those critical—if you're a theorist, maybe not because it's just good by themselves, it's okay, you know? Um, to make it, to make it impactful those are critical things to do, to those, um, you know, you've already…Data already exist in the literature. To work out, you know, you have parameters, you have conditions and limits in, in the theory that you've developed, to work it out in such a way that you can actually compare against someone's existing data. So it's critical in that sense to make a decision that you're going to do that. Um, it's also, if you can actually have something where you predict something people haven't observed yet, or haven't tried it because they haven't explored that particular region, um, then that's a, that's actually the more exciting point from the theoretical point…perspective. If you can convince someone experimentally to actually take your idea seriously enough to actually do the experiment. And so, um, there is an element, uh, that, and that's the critical way, in a certain aspect, to think carefully about, uh, how do I explain this in a simple way? Um, I did all this, calculated all this physics, all this math and so on and so forth, how do I explain it in a simple enough way so that someone else, um, can, can sort of understand it without all the detail. And understand it in such a way that they say, oh yeah I can try to, to see if I can see that experimentally. I think that's another important element in this kind of business as well is to kind of try and make your ideas clear enough so that someone takes them seriously enough that they want to do some experiments, so…

[Interviewer 3]: Make them simple enough even for an experimentalist to understand.

Expert: No, no, no, I didn't want to say it that way [Interviewer 3]! Not gonna quote me on that one, sorry. You know, just so that…

[Interviewer 3]: No, I understand.

Expert: So that it's obvious to someone, so they don't have to understand and follow all the detail, and you know, that's what I mean….I know.

[Interviewer 3]: I know. I've seen too many, you know, papers from Russian theorists where they're filled with equations you have no idea whether you can turn into an experiment or not.

Expert: Exactly, yeah. They tend to be that way, equation after equation, with that much detail.

[Interviewer 2]: Um, I, I'm curious if you could go into a little bit of detail about, for a specific problem you were solving you said you had, you were comparing to experimental data. Can you, can you actually talk about what the specific problem was and get into the details just a little bit for us?

Expert: Well, this was, this was a case where, um, people had some…you know, once we had the theory come out, people started to do measurements of the Microrheology and so on. And, of course, in the actual experiment there's a lot more, uh, other factors which are not in the theory and so on, and so, and so it's important from a theoretical perspective to try to appreciate the complexity that the experimentalists have to, um, deal with. And, and see if there aren't ways that you can manipulate your theory or take into account the factors that they have to take into account in the experiment. And, and at the same time, uh, try to encourage the experimentalists to do the clean, simple, uh, experiment which would unambiguously verify your theory. That's always, you know, they always say, yeah, yeah, yeah, sure , but, you know, that the real world's different. And so, um, in this context then, um, our first theories we had developed, we had neglected the fluid interactions for the particles—they

hydrodynamics its called. And so then a subsequent student put them back in, to see what the effect was, and you could see there was, in certain cases, a profound effect in what happens. And so, that's case where, you know, and the experimentalists would be hard-pressed to get rid of those interactions. And so that was a case where it was kind of important to do that to make that kind of connection and to make sure, again, that the whole idea is robust enough that it can handle these other issues and still be productive in that way.

[Interviewer 2]: Okay.

[Interviewer]: Okay. Um, so, I'm kind of curious how you decide at what point the, a theory is ready to publish, so to say. Sort of throw it out there. I'm sure it's different depending on whether it's predictive or describing results that are already out there, but…

Expert: Um, so when is it ready to publish? And he's not asking that for his own personal needs here.

[Interviewer]: No.

Expert: Um, so, um, yeah, that's a good question. When is a theory ready to publish? You know, um, you know, you gotta….Hopefully you got a story to tell, which, um, makes internal sense to you, that is, that, um, you know, sometimes I've done things in the past where, you know, it's sort of um, you know, I've probably done a lot of things which never got published, where for some reason I just didn't quite feel that I was fully confident in what's happened. There were too many lingering things which didn't quite make sense. And, and it might have just been my own failure to figure them out or to carry them through, or whatever else, but I was just reluctant to say…uh, something doesn't sit right with me. Even though, and, uh, there's been times where that was a mistake and someone else did it, and now I see it and understand it more clearly, but I was just, in my own sense reluctant to go ahead and do that. So, I think, thinking about those things, that means to me, then, when is it ready to publish is when I feel confident that, um, I understand all of what's going on. I understand it from different points of view, so that I feel more confident in the results, not just you know, the analysis that lead me down this path to this particular answer. I also understand it from looking at it from a different kind of perspective, um…

[Interviewer 3]: Can, can you, can you, can you be more specific on that idea of different kind of perspectives? What, say a little more about what that means.

Expert: Well, okay, you know, it could be, you know, uh, you know, and [Interviewer] has suffered through this with me, unfortunately. So you know, you're writing up a paper a draft, and you know then all of a sudden—I'll bring [Interviewer] into this not personally, just because it's also related—you know and you write something down in some way and then it's like ehh, you know there's got to be a better way to explain that. That doesn't, that's not the best, you know, and so, as [Interviewer] knows full well, we'll talk about it back and forth for weeks , you know, trying to come up with a different way to describe it and different description, and, and in the process, that would help us, um, make sure that we're on the right track. And, and you might have some results that you got by, uh, num[Interviewer]al calculation, and you might say let's look at it from a different way, maybe we can try to and this is a particular limit of the parameters, and so let's reformulate the problem with just that limit in mind, and see if…what that tells us, and how we can solve that one also and see if they agree. I recall a problem I had with a student many years ago in which he, I sort of worked out, I said the answer should be a half in this particular limit, and he kept not finding a half. And I just said, no go away and do it again. And finally he came and showed me a picture. And I said, oh, I…it's not a half. And we, actually in the process of that we actually, that I was so convinced, I was so convinced it would be half, we reformulated the

problem completely just to look at that particular limit. And, we were able to transform the problem into a different mathematical description which just solved that limit, and of course it wasn't a half, he was right. But you know, it was the sort of thing where we made sure we looked at it in all different kinds of ways, uh, before we were willing to go ahead to publish it. So, I don't know if that helps or not [Interviewer 3], but…

[Interviewer 3]: Some, but I mean, I'm picking up that you're looking at it in different limits, you're maybe looking at it with different representations like a figure. Um, I'm, I'm still not entirely clear about the idea of, sort of, when you say different perspectives. Uh, if, if this is what you mean, or there's some, you know, when, especially when you were talking about trying to figure out the simplest way to explain it, back to the experimentalist question. If that's, is that bringing in something different or not, is, I guess, the thing…

Expert: I don't think…I don't think you're necessarily bringing in something different, but, um often times you, uh, in doing something theoretically, you come to some results, some answer, and there are different ways you can express that, um, there are also different arguments, physical arguments you could make for why that is the proper answer. And it could be, you know, you followed down this one particular path, you had this idea, and you worked out the math and so on, and you get an answer. And, but then you could have stepped back and said, oh, you know, maybe I can do a simple scaling argument where I just sort of, you know, write a few things down and, and sort of show that that sort of has to be the answer, that it has to come out this way.

[Interviewer 3]: Okay.

Expert: Or it has to at least come out this way, perhaps the coefficient out front you don't know, but you can make some sort of arguments that, sort of, now that you understand what the basic things going on are, um, how it sort of has to be this way. There's a lot of things done in, in physics these days which are called scaling, I don't know if you know about this, but, so you can do some simple reasoning what…how it has to behave to this power and whatever else and so on, and those things you can get out without the detailed calculation, um, and so oftentimes we approach things from that perspective as well.

[Interviewer 3]: Okay, that helps, yeah.

[Interviewer]: More questions?

[Interviewer 3]: Go ahead.

[Interviewer]: Okay. Um, I don't, I, I feel like I'm filling in the gaps too much here, so if there are things you feel we haven't covered.

[Interviewer 2]: Um, so, I, I guess in, in, in, for, for the, how do you decide when to publish question. If you can make it really concrete and think about, like, the first paper that you published on this project. And, like, how did you decide that that, you were ready to send out?

Expert: Um, I think we got, we basically got the complete story. We could cover the, the, in this context the full parameter range from basically no external force into full external forcing. Um, we had also backed up to be able to start from the full complicated problem and derive the reduced description that we had to do it. We also had, um, in this context, we were able to, uh, sort of, solve the full problem and, at least by separation of variables in this context, and write down the answer. We were also able to

solve it by some asymptotics in some different limits. Um, and so we had all those pieces came together, and it seemed to make a complete story. Um, and then I think, um, there were many other things that one could do. But those were projects in and of themselves. And so, it was a time to say, call it enough, at this particular stage, and save those other pieces for separate pieces of work, rather than continue to do that. So that's probably, a, another important element of when to publish in that sense. Is, is to, when do you, so this turned out to be a problem which opened up a lot of things that we could go on further, but at some point you gotta say okay we're going to stop now and get the idea out, and you know, those other pieces of work are interesting and will be fun. But we shouldn't wait and hold off for that to happen, and so we should get this out now. And so that's oftentimes, um, if it's, particularly if it's a problem which you think has, um, has some legs, some future, some other things that, that at some point you gotta decide, okay does it make sense now and, let's get it out there and be concrete, and worry about those other issues later on.

[Interviewer 2]: Mhm.

Expert: Yeah, that's an important…yes. You can always, there are always more things to worry about. So you have to cut it off at some point and say that's enough, you have to save those for the future.

[Interviewer 2]: Mmm, I wanted to, so on that first paper, what…were there any particular challenges that you encountered as you were solving it? And, and…

Expert: Uh, apart from figuring it out? No.

[Interviewer 2]: Yeah, right, right.

Expert: Um, no. And in publishing, the publishing was fine. I guess we had to also decide upon what journal we would send it to, so there's a choice in that regard. And this was one where there was a fair bit of, um, a fair bit of logic and description necessary. So it wasn't something which could be distilled down to a four-page PRL, that was not going to be this kind, it was, it needed more, it needed more to describe it and I think the, the audience would need to have more information than just four pages. And, so, it was something that we decide upon something like that. Um, we also didn't know how important it was going to be in terms of opening up, you know, we didn't really appreciate it at the time. Uh, and so it went to a more traditional journal which we had had some experience with, that people who had done, we thought people would be interested in this kind of a problem. And so that's how we chose that particular thing, and I think it went through pretty fine. I don't think there was any real complications in the review process, it seemed to be okay. So that one didn't seem to run into any issues. It's not always the case, but that one didn't. Go ahead.

[Interviewer 3]: But it does sound like in your thinking about how to lay out this story for people, you came to have, make the decision that, okay this has, this is going to have to be in a longer paper, uh.

Expert: That's right, absolutely, absolutely. Mhm.

[Interviewer]: I just saw this question I wanted to ask and then…I can't find it.

[Interviewer 3]: Well, while [Interviewer]'s looking for his other questions, maybe, talk a little about the, um, you said this led to, lot, you know open up lots of other questions, led to lots of other things. Uh, sort of, you know, what, what…how did that process work? I mean, you know, you're sort of working away, did you suddenly realize, oh if we put in this parameter this would be a whole bunch of new stuff?

Or was there, I mean, any…how did this questions occur to you, how did you decide which ones to pursue?

Expert: Yeah, so what happened was, because we, uh, you know in this process of trying to distill this, uh, what was a complicated question down into something simpler, it led to a, a different way to, sort of, probe materials in terms of this Microrheology aspects of it. And so that was just a different perspective people hadn't really taken on these kind of problems. And, um, so once we figured out, and it turned out not to be that hard in some sense, I mean mathematically and so on, and, and that was, gave us an opportunity to incorporate other physical effects relatively straightforwardly. Uh, both in terms of, um, how they would be described mathematically as well as how we could understand their importance. Um, we could put the hydrodynamics and fluid mechanics back in. It was also something that led naturally to be able to do a lot of simulations of it, so we can, have the same basic principles but don't have to make the, some simplifying approximations. You can relax a lot of those approximations, at least in the computer simulations of these kind of things, and so it led to whole host of other things that one could see and do. Um, it also led to a whole business of, of self-propulsion because we could see that the structure that this thing allowed us to think about, um, how the other, uh, particles in the suspension influenced the behavior of the, of our test particle. Um, we understood how they were doing that, how they reacted, and what their influence was, and we understood then, if you could create that distribution by some other means, um, you could also have, um, self-propulsion. And that led to a whole other aspect as well. So it turned out to be just a thing that opened up a whole, whole possible way to think about a whole class of problems. Um, so it was very fruitful, very beneficial, I, I, you know I can't tell you that's what we…there was no great insight at day 1 that that would happen, not at all okay? It's something that evolves organically over time, and as we understood more deeply about, about what we had done, the approach we had taken, how that could be extended and applied to a variety of different simulations. So it's just something that evolves.

[Interviewer 3]: Okay.

Expert: I took a success a story to tell you about. I could have taken a non-successful story which would then have ended the conversation 20 minutes ago.

[Interviewer 3]: No, right, we understand.

[Interviewer]: Alright. I remember what my question was. It was, um, about a particular sort of bottle point in the process where you…has, has there been a circumstance where you sort of write down and come up with a workable model, um, and then you go back and do, work out all of the details and it turns out that the simple model you wrote down, while, even though it predicts things that make sense and it looks nice, it's actually wrong in some other way?

Expert: Um, yeah, that's possible. I'm sure that's happened. Um, I don't, I can't think right now the detail of a case, but I'm sure that that's true. That, you come up with situations, you go back and examine it more thoroughly, and you realize that, um, it's not quite what you thought it was, uh, for sure. Um, and, um, so then, um, so when that happens, then the, then the challenge you have, uh, is to, okay, how can I rescue this thing that we just spent all this time working on that's now, all of a sudden, got some terrible flaw in it. How do, you know, because then you start to wonder, um, you know, come on it's doing some things right, it can't be all that bad. You know, and so on, so that gives rise to a lot of anxiety and late nights thinking about stuff. Um, you know, is it really all wrong, or, or it can't be that wrong because some things are working out right. So that, that, I guess that's, that's all part of that

process of, um, trying to reexamine things from all the different kinds of perspectives and angles, and stepping back, and…Um, but I'm sure it's happened where, all of a sudden, it seems like, it's, you know, an assumption, a fundamental assumption that you made is not right, um, despite the good looking results, right. And so, then, then when that happens, um, what do you do? One is you just abandon things and say, well it's wrong and just shut up and do something else. Um, but if you think the outcome's looking promising then you have to ask yourself, you know, maybe, maybe your derivation that it's wrong is NOT correct. And so, that, reexamine, keep examing that and maybe discover there's a different condition under which it applies, you weren't thinking about originally, and so on. So that's how I go about that, how that part of that examination from different perspectives comes into play, I think.

[Interviewer]: Okay. [Interviewer 3] is writing things down. Um, so this…

Expert: Never give up! Never give up!

[Interviewer]: This is something I'm interested in, and this is a loaded question for this particular scenario, but it was…um, wondering if there are particular difficulties that you know students have when they start out working in your group?

Expert: Um, you know, I, I, um, they all have difficulties in different ways starting out. Um, um, so I, I try as you probably know, to give problems which are, um, um I think, you know, sort of what I call a warm up problem. Basically something which is not, um, not going to be their thesis, may not yet, and may lead to it, may not even lead to it. But, just sort of get them, get their feet wet in the area, because everyone comes in with different backgrounds and different skill sets, and they have to learn a lot of things. And it's, it can be very daunting to try to just sort of , you know, confronted with this whole new field, just sit down and okay, read. And you get really bored reading and you don't learn anything. It's sometimes better to, to start doing, start working. And so, but you can't jump into something which is too complicated because you don't have all the skills necessary to think about it. And so I try to find problems whereby students can make headway--they're not that difficult. And then sometimes they've led to really interesting results and then that was just something they did that's finished and over, and now we get on with what we intended to do. And then, but to answer [Interviewer]'s question in the course of doing that, I think, is where I try to, uh, get some insight into what aspects of the student's background are, uh, missing or what parts of, um, what they do, are they really good at and enjoy? Okay because everybody's a bit different and some people like this or that or so on. Some people are more comfortable with doing computations versus doing analytical theory, and so I think it's in the context of this warm-up problem that I try to get a sense of, uh, where do I think it's going to be the best fit for them, and then, uh, try to tailor the future thesis problem based upon that insight I get. And sometimes it, sometimes it's right, sometimes it's wrong, so, see. But that's, that's how I try to do that and then see if I can't adjust the topic or the way we approach the problem that's better suited to that particular student's skills.

[Interviewer 3]: So that's looking very much at the individual and the match to that.

Expert: Right.

[Interviewer 3]: Um, in terms of trying to think about things you've seen that are more general. I mean, one you sort of mentioned in passing that's, that's uh obvious, and maybe they all are, of you know, the if it's too complex a problem for somebody who's starting out, you know, or every body who's starting out, you don't want to put in too much complexity. But can you think of any other things that you sort of

see as general areas where you sort of, you know, when, when they come in and report something, you sort of think okay I'm going to have to check this, because that's where students often go wrong.

Expert: Um. Let's see, apart from making them check the units of calculations, that's always a good one, um, I think, I think I do make them, in terms of checking the limits often. In terms of, you know, if I remove that effect that you just spent six days working on, does the answer reduce back to something that expect it to be or not. Um, I think, I think students need to learn that. Not everybody has this sort of self-check mechanism inside them when they come along that makes, they always should have this self-check that says I got to make sure this recovers things that I know as true. And I think students don't often have that, so that's something that I try to insist upon, and, and hopefully by insisting upon that they'll pick that up and realize that's something they should be doing on their own all the time. You know, and even to the point of, you know, and this, this may sound strange, I don't know how you guys think about things, but you know, even an equation has units in some sense. So you can know whether you wrote the right form of the equation down by whether it checks out, and so, students often don't have that kind of a check. They are just sort of so happy they wrote an equation down that they just run with it. So I do see that and when I talk to students and try to, um, that's a, I think a gen[Interviewer] issue I try to get everyone to think about those, along those lines. Um, and that's where I would see that, when we first start out working together.

[Interviewer]: Okay. Any sort of, final questions from anybody?

[Interviewer 3]: Seems pretty good.

[Interviewer 2]: Yeah.

Chemical Engineering Industry 1

[Interviewer]: So, we're interviewing you as part of a project to identify how experts think as they solve problems during their work. Um, so our goal ultimately is to identify what students ought to be learning to do in order to improve education. So, today I'd like to learn about how you solve problems by having you, uh, think about a problem you solved in, uh, chemical engineering design, um, or some large-scale project you've completed. Um, and as best as you can, walk me through all of the detailed steps and with particular focus on, kind of, the decisions you were making as you were going along and solving this problem.

[Expert]: Okay, sure. So, this is, um, so there's a process in the refining business that's called catalytic reforming. Basically that's taking C6, C7, C8 hydrocarbons, ran them over a catalyst at high temperature, and that promotes the conversion of straight chains to rings. So, you're going from a straight chain linear or isomer to a ring structure—you make benzene or toluene or xylene, as you're doing that. Benzene, toluene, xylene have much higher octane numbers than…heptane or hexane, right? Uh, heptane or octane. So, normal paraffin octane, right? So, this stream goes from being pretty low in octane number to quite high in octane number, and that means that you can then meet the demands of the market for high-octane gasoline with the product of this process, okay? So, and people have been doing this since the early 50's. Part of the problem is that you make coke. And, so the catalyst gets fouled, and there's a certain period of time you can run before you shut down, regenerate by burning the coke of the catalyst and doing other things, okay? Um, starting about 1960, the people who licensed this said, "you know what? We should come up with a way to do continuous catalyst regeneration." And they worked on that for a long time and came up with this way to do it in the 70s—early 70s—and *clears throat* by doing that they could…they…so, you had this thing where now you could continuously regenerate catalyst. So, um, you didn't have to worry so much about process conditions that gave you lots of coke. So, um, people would run it at, say, 400 lbs pressure in the reactor system, because that would suppress coke formation. But, it also gave you less….less reaction, so it was not as favorable to the hydro…uh, hydrodecyclization—making aromatics—but it was a compromise between making less aromatics and less coke, and giving you a run length that you could live with—9 months, 6 months. Okay, so, bang. We now have cheap…we don't have to do this, we can run at lower pressure and that gives us, um, way better yield, and so, we get—for the same unit of feed going through the unit—we get higher octane numbers than we got before. Well, okay, that's really good. Problem was: when you got to the end of the process, and you eventually cooled the material that came out of the reactor system and did a liquid-vapor split, a pretty fair amount of the liquid product that you wanted ended up in the vapor stream. Because the pressure was so low, that a lot of that vaporized, okay? And you make a lot of hydrogens every time you take a molecule and you pull some hydrogen out of it to make it from paraffin to aromatic—you get three moles of hydrogen for each mole of material you…you work with. So, a lot of extra gas in the system. That means the partial pressure of the hydrocarbons is much lower, that means a lot of it vaporizes at the conditions in the separator system. So—what to do. You don't want to throw that away, what to do? And, the folks who licensed the process basically came up with the idea that you would compress the gas and run it through a low-temperature system to condense out the liquid, um, that you wanted to recover. Very straightforward, right? Raise the pressure, lower the temperature, you'll get more liquids coming out. And they offered that as a solution either for new units, or for old units that you were converting to this new continuous process. Alright. So, um, that's really brute-force. So, when we were building one of these systems for a new refinery in Thailand in the early 90s, I looked at that and I said: "gotta be a better way." And, so, before you can take this material and put it into a catalytic reformer, you have to get all the sulfur out of the feed. And so you have the feed pretreatment unit, is where you react hydrogen with the molecules that are coming in and then extract all the

sulfur…make H_2S. And so I looked at it and I said, "Gee, you have a high pressure system is this Naptha hydrotreater at 7 or 800 pounds pressure. Um, you have feed coming in which is a good absorber oil. Why don't we take the hydrogen…so the off-gas from the um, platform and compress it up to pressure, run it counter-current through the feed in an absorber column, take all that material out in the absorber, run it through the Naptha hydrotreater, and recover the liquids that way?" And as a bonus we get a very, very pure hydrogen straight…because pretty much all the stuff that's not hydrogen gets absorbed into the feed. Plus, it absorbs enough hydrogen to meet the hydrogen demand of the first process unit. Um, am I…do I need to draw it out, are you okay?

[Interviewer]: I'm okay.

[Expert]: Okay. So, it was all, you know, "oh that's, gee, mraw mraw mraw, we've never done that before." So we sat down with our engineering contractor and said, "please run this simulation. Let's see what it looks like, let's compare it to the conventional process." "Oh wow, this gives us higher hydrogen purity," because we need the hydrogen for other things in other units. The less non-hydrogen you put into them, basically the less um, um…less bleed stream you need to um, make the impurity. So you have a circulating loop somewhere else of hydrogen, right, a recycle stream. And somewhere there has to be a bleed stream to keep the purity up. Well the less non-hydrogen you have going in, the less bleed stream you need, that means the less hydrogen you have to get rid of as a, as a bleed. All things better. And, we looked at this and it was, "Wow, this really does work much better than the standard, um, solution." And that's what we built. And, um, runs it cheap, not a problem, um, and so that was at…at…a solution to a problem that really didn't exist as such, it was just, this is a better way of doing it, okay? It uses less energy, you don't need all that refrigeration…money spent on refrigeration. Um, you don't need the refrigeration compressors system and everything else. Very simple, easy as pie for the operators to operate it, and um, so that was…that was a step out from what the normal solution was. Mmm…nothing there was anything that chemical engineers don't know how to do that isn't done elsewhere in other types of recovery operations…where you have a gas and an absorbed oil stream, and you pull stuff out of the gas into the absorber oil. So, nothing unique there. But, a better solution. And it was a better solution becau…that we could employ because we were building both the pretreater unit and reforming unit at the same...it was a brand new refinery. So we could tie this to this and get the, um, desired effect. So, an example.

[Interviewer]: So, just for me to clarify. So, you're…you're decision to…to take this and use the, um, use the countercurrent reabsorption, so that…you just made this decision, kind of, based on the fact that this is something that we do in other processes?

[Expert]: Yeah, yeah.

[Interviewer]: Okay.

[Expert]: It was: "why are we doing it this way as opposed to the brute force method that's in there now?" And part of the answer to that is that the people who license this technology, when they were retrofitting it to an old unit, what we were going to do wasn't quite possible. That was too complicated, so they wanted a stand-alone solution. We have a recovery system we tack on the back and *washes hands* done. And not many people are building new plants, so this wasn't an alternative that they considered.

[Interviewer]: Okay. Um, were there other solutions that you considered to this problem?

[Expert]: No. So, there was the standard one, and there was the idea that I proposed, um, and I must say, much to the surprise of our engineering company who was doing the simulation, design, etc. etc., was, "Oh, wow, this really is a lot better."

[Interviewer]: Hmm. So you didn't encounter any difficulties, kind of, after, you know…after thinking about this idea?

[Expert]: Well, the main difficulty was "I want you guys to study this as an alternative." "Oh we're busy, blah, blah, blah," you know? "We have a solution that works, don't bother us." The answer was, "no, I think this is better." And because I was in charge of the…of the process, the whole project management…I was deputy project manager, and I said, "No. Do it."

[Interviewer]: I see, and so did…

[Expert]: You don't typically get that flexibility.

[Interviewer]: So did this require looking up, like you know looking for any new knowledge, like going out and seeking…

[Expert]: Oh, no. They just went and did a simulation and whatever the equivalent of ASPEN was, they compared the two and said, "what do you know?"

[Interviewer]: Okay, um, so that's interesting. And then, did…is that still the process used to this day?

[Expert]: Well yeah, the plant was built, that's how it works.

[Interviewer]: Yeah, well that's true, it's still operating. Um, so, I'm interested then, if, at any point in your career, you've, um, you've encountered design problems like this where you did have to, kind of, go beyond the knowledge you had learned during your education and, kind of, you know…something that scientists do a lot is when they're encountering problems they go and read literature because they just don't have the knowledge to tackle a problem. I'm wondering if that's something that's ever come up.

[Expert]: Oh, yeah. So once upon a time in my career I worked for a phosphate fertilizer company, and my job was to find other uses for things that were not…so when you make phosphoric acid you make other things besides. And the question is…what can we… can we add value or valorize other things besides that we make? And so, to make phosphoric acid, you react calcium phosphate rock with sulfuric acid, and you make…and in most simplest terms you make phosphoric acid and calcium sulfate. Um, but there's a lot of fluorine in there, so you also make HF as a byproduct. Uh, there's also silica mixed in with the calcium phosphate rock, and so all that silica reacts with the fluorine and makes fluosilicic acid. Okay. What do you do with fluosilicic acid? You neutralize it with calcium hydroxide and throw it away. Okay? So, it's just always calcium fluoride, relatively inert, you throw it away. So, gee. Fluorine's an expensive material to buy, could we do something with the fluorine that would, um, add value to it? We're sure as hell not going to make HF, that's just far too dangerous for, an, an, an, operation where you basically mix acid with rock. And, uh, it was pretty simple…I don't want to use the word agricultural…but it was not technically challenging equipment we're operating. It wasn't like we were working in a biology plant where the operators need more knowledge. Uh, and um, this…the, uh, phosphoric acid, you concentrated a bit and when you concentrate you drive off the HF and, um, so, um, it's all very simple, very standard stuff. And so, um, I had to look and say, "well, okay. What do people

use fluorine to do? What might we be able to do with it? Uh, and what do we have in the plant anyhow that might help us?" Okay. And so it turns out that uh, well, so when you make phosphoric acid, you really don't sell phosphoric acid very much. What you do is react it with ammonia, and you make monoammoniumphosphate, diammoniumphosphate…and that's fertilizer. Okay? And that's sold in, many, many tons. And so we had ammonia in the plant, and so we're considering making HF. And, so, I scrounged around in the literature and it said ammonium bifluoride is used to make, um, you know…is something you can make from this. So if you took that fluosilicic acid and ran it through and ammonium system…basically scrubbing system, the ammonia and the fluorine would react to make ammonium bifluoride. Okay, ammonium bifluoride is a little bit used in fracking wells. Uh, with a lot of siliceous rock, you pump this down the well with fluorine, eats away the silica and opens up the spaces. Um, we don't want to make ammonium bifluoride as a product. It's dangerous to make, and it's dangerous to handle, um, the bags are hazardous waste, that you put it in are hazardous waste. Forget it. But, it turns out that potassium bi…potassium borofluorate, KBF_3, is, um, used in making aluminum to improve ductility. So, it's a specialty. And, it turns out that you might be able to take ammonium bifluoride and react it with boric acid, and make fluoroborate. And if you can do that, then you can react that with KOH and make potassium fluoroborate. And, so, um, we engaged, um, a little research lab, a contract research lab, to do this for us—to take this idea I had, test it out in a lab, and see if it would work. And the answer was, "my goodness, yes it does!" So, you could make potassium fluoroborate from spare fluorine through the ammonium bifluoride route. And we went around and we tried to sell that to a number of people, um, and um, you know it was interesting. Uh, people thought, "you know, that's a big deal, but there's no shortage of this right now. So, investing in something that would make this for a market that's already well-supplied…unless it could be made for a whole lot less," and the answer was, no it couldn't. So it was a way to make more than you used to, but we wouldn't necessarily be able to sell at say, 80% of market and attract customers, and still be profitable for us. So, it got us as far as the process design stage, and as soon as we tried to sell around to various people, and um, specialty chemical makers who make this product sold it as an alternative that would make them more volume at a competitive price. And, um….not enough in it to do that. So that's my…that's one where I actually needed to go figure out, find the chemistry, find the…what's the market for this, and come up with a way that maybe you can actually do this based on my knowledge of chemistry.

[Interviewer]: Okay. Um, and so, uh, when…at what point during that process did you kind of decide…at what point did you decide that it wasn't something worth pursuing ultimately?

[Expert]: Well when we couldn't get anyone to…when no one saw it as profitable enough to do it. We took it to England to LaPorte and other people, and sat down for several days, and discussed and they said, "you know, this is a good idea, but it just doesn't have enough Delta for us to invest in something that's new, unproven. So forth. And, you guys are, are, are phosphoric acid makers, you're not specialty chemical makers. So, mmm, we're not so sure that you're the best people to do this." And you know, we talked about, "Well, you could build your plant in our works and do this." And it was, "Ehh, that's too much overhead."

[Interviewer]: I see. So, I'm interested then, um, it sounds like. Well, actually I'll start this while I actually try and formulate what I'm thinking about. But I'm…would be grateful if you could kind of comment about difficulties in problem-solving that you've noticed in people you've had to train. And, you know, being kind of as specific as you can. What did you notice when people come into these projects? What are issues they commonly have?

[Expert]: Okay. Um, so I'm going to start with students, okay? When you do a design, at least as I perceive in our business, right? You basically, everything happens in equipment, okay? And so…um…if I say to you: I have a pharmaceutical material that's a nice and green slushy material that's coming out of my fermenter. I've chewed it up, taken down all the cell walls, and I'm trying to extract the material out of the fermentation process, okay? And I want to run it through my extraction system at a constant rate. How do I do that? Mwaw….well you can pump it. Okay, good, excellent. How am I going to control the flow? "Well you're going to put a control…a flowmeter on it and you're going to control it." And the answer is: Hm. First of all, what kind of flowmeter? You really don't want anything that's going to be in contact with the fluid, because when you do clean-in-place you have one more thing to clean that's in the pipe, and I really don't want to do that. So, I need something that fits outside the pipe—sonic flowmeter, magnetic flowmeter, something that will do that—and then how do I control the flow? Well, probably, you need a variable speed driver on your pump so that you can increase or decrease the speed depending upon the…the, the, the flowrate's going up, you want to decrease the speed to maintain the flow constant. "Oh, hmm. How do I do that?" Or, is it better to say I'm going to buy a positive-displacement pump that always pumps the same amount, and it just…everything else downstream to handle a constant break in flow to everything downstream. Which do I choose? And, you know, that depends on a lot of other factors. But, the idea that I'm taking this broth, I'm running it through my counter-current extraction unit…in order for that to work, I need to make sure the ratio of this…of the feed and the solvent that I'm extracting into…that ratio is constant. How do I do that? Right? If it was hydrocarbon, the answer is simple: you put a flowmeter on each stream, a control valve on each stream, go through a ratio controller. Bang, done. But pharma? Not so simple. And so, if you're developing people to think about these things for process in general, you know the ratio of control…you know you want to control the ratio of one liquid to the other, one stream to the other. That's a given. Same thing with an absorber, right? You're putting everything in, you want the L/V ratio to be constant. You need to measure both flows and control one relative to the other. How do you do that? So, the concept of ratio control is something you should teach. And then people need to think about, "how do I apply the concept in the unique circumstances of what I'm trying to achieve here." And, when we teach control in many universities, what do we teach? Do you remember?

[Interviewer]: Laplace transforms.

[Expert]: Right. Relevance? Zippo. So, when people come to design, and I'm trying to talk to them about, "Okay, well. Here's what we…here's what it shows in the block flow diagram, how do we physically implement that?" They have to be taught first about the concepts of ratio control, you know, ratio control and so forth, and then about possible ways of implementing the concept. Um, and so, because they don't have that, it's more difficult for them to paint a mental picture.

[Interviewer]: So it's more difficult to apply this…so..

[Expert]: They can't even apply it…

[Interviewer]: because they don't know.

[Expert]: Yeah.

[Interviewer]: Yeah, so that…in this class they're kind of being put in the situation where they're trying to use knowledge they simply don't have yet. I see. And so, that's…that's interesting in the context of the class because I'm wondering if, for example, if you somehow had more time to do this in the class, um, do you think that seeking out that knowledge is something the students would be capable of doing?

[Expert]: Capable of doing?

[Interviewer]: Yeah.

[Expert]: Yes. Likelihood? Not so much. My experience with my own…as a student myself, uh, from any student I've pretty much interacted with… gee, there's stuff I don't know, I think I'll take my… you know…I've got extra time, I'll go and investigate. It's much more: this is the course. Uh, unless the course specifically instructs me to go and find stuff out, I'm just going to follow the syllabus. It would be nice. Uh, I don't know how graduate students do things in that…but I think grad students, you know, okay the first thing we want you to do is read these 47 papers that have been published on the topic and educate yourself about people's thoughts on this and what they've found out, and so forth. So that puts you in a very different spot than an undergraduate, trying to learn the fundamentals. But, for a grad student, I think it's a very narrow focus, I could be wrong about that. So, as a recent graduate…grad student, was that your experience?

[Interviewer]: Um, so, it was. I have a really nice story because my first research meeting with my graduate adviser was, "I want you to think about this. This is the name of a person who works on it." That was the duration of the meeting.

[Expert]: That's pretty open-ended.

[Interviewer]: So, I mean, he knew my background, knowing that I had some kind of research experience before, so…

[Expert]: Right, you worked with [Name], right?

[Interviewer]: Right, so from his perspective he assumed that I probably knew enough to take that and run with it. Um, but it's still the same kind of process where one of the very first things you do is go and seek out information.

[Expert]: So, see what other people have done and what conclusions they've come to, that all informs your way of looking at things right? So you didn't say, I want, here's a problem, don't look at anything anyone else has done, and come up with something de novo, come up with a solution.

[Interviewer]: Right, and that's not how process design works either. Like you were saying, there are people who license processes.

[Expert]: Right.

[Interviewer]: So, when you're thinking about a plant, a lot of the time you can get a process license to do most of what you need.

[Expert]: So, so, that's true. That doesn't mean development stops.

[Interviewer]: Hm.

[Expert]: So, about *weird noise* the early 80s, the people who licensed ammonia technology, they formed a working group and they asked how can we make ammonia plants more energy efficient—how can we use less energy per ton? And they went through it step-by-step and said, "okay, hm. What if we

were to do this…what would, how would that change things? What would… you, know, here's this step, is there anything we can do in this step that would reduce the amount of circulation or the amount of energy or the amount of whatever, resulting in less energy consumed in that step?" And they went through the process and came up and said, "Here's x number of things that can be done. The easiest one to do is this, which is a fairly simple retrofit or change," to "here's one that's really tough. And, if you're going to build a new plant that might be a good idea." But to try and do that in an existing plant, no. And one of the problems we chemical engineers face is: you spend a lot of money to build a process plant. So, you know, you just spent $400 million to build this, you say, "Oh, you know, I have something a little bit better that gets you 1% more yield." That's nice, *laughs*. But, I will give you one example, um, and I think it Analin. Analin used to be made in certain way. And someone came up with a new catalyst that allowed you to take, the, uh nitrobenzene and hydrogenate it in a fluidized bed reactor, and that cost so much less to make than the old technology, that pretty much, one by one, people built new plants and shut the old ones down. And, so, you went from doing it this way to doing it that way and that's a complete change-out. Over, x years. Because this was SO much less expensive than that. But that's…that's one of the few that I know of that actually…and I may be wrong about Analin, and In fact I am it's acrylonitrile.

[Interviewer]: I see.

[Expert]: I guess that's right. Anway.

[Interviewer]: So, my understanding of how this works, and also remembering back to what I learned is that there…essentially the constraints in engineering…it's not necessarily that the process about how you go about solving a problem is fundamentally different. It's that, when you're thinking about this from the business side of things there's one overall criterion that's always trumping everything else, and that's basically ROI. So, you know, if there's a…there might be a better way to do this and the scientist is interested in the better way to do this, but the engineers and the managers are interested in, you know, is it worth the investment.

[Expert]: Okay, photovoltaics. We all know how to do a photovoltaic cell. Gee, what if we could get one that had twice the energy absorption, twice the energy generated, uh, as the current technology? Oh, that sounds very interesting. Yes, but it requires platinum as the…oh, never mind. Right? Yeah, so there may be things out there, but they have to be better than what's now, not only in terms of performance, but in terms of, what does it cost to make it and run it.

[Interviewer]: Right.

[Expert]: So, yeah. And, um, my daughter is involved with drug trials. She works for a company that runs drug trials. And the FDA rules are, if you have a drug, if you have some sort of treatment, right, whatever it is. And there's all, always something being developed, right? The trial has to show that it's at least as good as or better than what's out there now, otherwise it doesn't get approved. And if it's just as good as what's out there now but costs twice as much, guess what?

[Interviewer]: It doesn't get used.

[Expert]: Yeah. That's nice, but so what? And so, yeah…cost…sorry, not cost, ROI.

[Interviewer]: So, where in industry does this kind of bridge happen? Where, I'm kind of thinking of, there are people in universities and in some…somewhat in R&D departments doing novel, just, how can

I accomplish X? And so, then, the engineers are, “Okay, that’s nice, but it’s not profitable.” Who’s doing the work trying to find ways that it can be done profitably?

[Expert]: So, companies used to have R&D departments. Uh, some still do. [Company] still certainly does R&D. And they’re doing it more on product design, I think, than process design. Um, because I think, if you’re going to make shampoo and mix this with that and dissolve this in that, and so forth, and so on…that’s not so…you’re not going to necessarily do something so different that you can’t even use existing equipment or similar equipment or things. And so the question is, do you get better performance from the material. And so now it’s the raw materials and so forth and so on, and not so much as we’re going to change the process to use less energy and get to higher yields or whatever. And so, in those instances I think that corporate R&D is out there, and um, I know that head & shoulders has been around for…since I was in high school. And they’re still trying to improve it. So, there’s always evolutionary improvement that’s going on in R&D departments. And, I guess, they’re trying to identify…what can we do to make this performance better or get the same performance at lower cost per unit?

[Interviewer]: Mmm.

[Expert]: And, um, the process industries that make large volumes of chemicals or refine oil or whatever, they’re also doing that. But, they’re in a much different situation, so, if you’re, uh, Tom’s technology company. How many of these things do you sell in a year? One. Less than one? So, how much can you afford to put into R&D to say, oh, well the next customer to come in, you definitely want to come and by my technology solution as opposed to their technology solution because it…I can demonstrate to you how much better it is. That’s tough.

[Interviewer]: Mmm.

[Expert]: Um, some researcher at some university might say, you know, I’m going to come up with a better catalyst to achieve the same result. Okay, interesting. And maybe they do, maybe they don’t, but let’s suppose they do. It still has to go through the same development cycle of, “if we employ this catalyst, what’s doing to happen?”

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[Interviewer]: So, we're interviewing you as part of a project to identify how experts think as they solve problems during their work. And our goal is to identify what students ought to be learning to do in order to improve education. Um, so today I'd like to learn how you solve problems by having you recall a specific problem you have solved or a project you've completed during your career, and, kind of, as best as you can walk me through all of the detailed steps of this particular problem. Um, with particular focus on kind of the decisions that you made as you went through it.

[Expert]: Mkay, I'm thinking here for a second about a good problem. Um, like, clearly this is going to be around, um, *sigh*, kind of mid-to-late career. Um, look, one of the things that we get into is decisions around, um, and I'm talking from an oil and gas perspective now, in off-shore. And you go find something, you drill an exploratory well and you find something. You drill some appraisal wells to kind of define it and reduce the uncertainty around it, and then you make a big decision and spend a bunch of money to do development. And so, that's kind of the problem that I'll address here today. And the dilemma here is: you know money has a time value. So delaying, um, delaying that investment decision, um, costs you something in terms of the time-value of the money, but at the same time you're dealing with uncertainty on the other side of the equation. And how uncertain is this thing? And, and I…I've gone through that process multiple times at this point, but a number of times with tricky things, sometimes with success and sometimes to failure. Um, I, and one of the…and…well I guess I'll ask you a question before we get too far into this because I don't want to take you down a rabbit hole here. Um, are you looking at problem-solving in general, or as an individual, or as a team, or…or does it really matter? Because I…most of the examples that quickly come to mind in my case are inevitably team-related things. They're not individual, I'm trying to solve a specific engineering problem in this particular context. I'm trying to solve something bigger than that, and I may be leading the team, I may be a member of the team, but the problem is bigger than me by itself. Um…

[Interviewer]: Right, and so those problems are certainly fine because that's realistically how it happens for most people I would say.

[Expert]: Yeah, it is.

[Interviewer]: And so…but I do kind of want you to focus on kind of, you know, you can talk about things at the team level—kind of the collaborative decisions you made—and then what individual role you played in that as well.

[Expert]: Sure. Sure. And a large part of it, quite frankly, is and…and frankly most of these decisions were done, um, in, in a team context and where I…and most cases I was some kind of a leader of the team. And, and so, a lot of what you spend your time on, frankly, is the dilemma of, um, getting diverse opinions from other people, and not getting locked into the…the, uh, what do I want to call it, the fallacy of the one individual who speaks the loudest, but not necessarily has the right opinion. And, um, I mean I…we got into this at, at one of the Advisory Committees, you know, what is diversity? Diversity—too me—is opinions. It's people with different perspectives to solve the problem. And, and a lot of these problems involve—because they have high levels of uncertainty, I mean just to be clear, we're dealing…I mean. I drill a well and I've got an eight-inch hole in the ground, and I can measure maybe a foot around that, so I've got a three-foot known…a three foot known. In a body that's 200 feet thick, and a mile wide, and 3 miles long. And, and I can drill another well and get the same amount of data somewhere else, and it's inevitably the homogeneity/heterogeneity question that determines, you know, "Is this this

all connected together, fundamentally" is the question you're trying to ask. And there's some other data about what kind of recovery I can expect from this reservoir, but the, you know, how much pressure do I have, am I above or below the bubble point—those are all factual things you can answer. But what you're left dealing with at the end of the day is the homogeneity of the thing, and, and, and, and, d…does the model that you have really represent the reservoir and can you extrapolate thing. Because I'm about to make a multi-billion dollar decision, and if I get that wrong I've blown a lot of money down the drain. And we've done it well and we've done it badly. And what do you have to do to get through that is a combination of building models to represent what this thing looks like based on the data that you have, testing the boundaries of these models. I mean these are often million-cell kind of models, um, and you're basically doing transmissivity at the boundary of each cell in the model. Um, but how you model the, um, the, um, that homogeneity at the end of the day is critical. Now, one interesting dynamic that I would put out, throw out there, is a group of *sigh* eh…and, and I forgot left brain/right brain, but engineers tend to be very analytical, methodical, and what not. Geologist on the other hand tend to be—I mean we used to joke when I worked for [Company 1] that the windows in the building didn't open because the geologists would float away.

**[Interviewer]: ***Laughs*

[Expert]: Um, they're the creative souls in this process. And the point I'm trying to make is you need both, and you need to bring both of those perspectives to play here. So, when you're trying to solve this problem, um, you want people to have crazy thoughts. Um, a…another, um, uh, concept in this whole thing is negative authority: who was negative authority and where do you want it to be in the system? And, and in cases like this you do not want negative authority…when I was a young engineer and I went to work over a well, um, I had lots of negative authority: I could choose to recommend doing it, I could choose not to—at the well level. But at the development level, um, you don't want that person to have the ability to stop the thing. You want to have diverse views, and you want the occasional crazy view. Now that the key from a problem-solving perspective is: how do you filter the crazy views? How do you figure out what's a crazy view and what's an interesting perspective on the problem—and maybe that person's right and you need to go test that and get a piece of data. Um, that's always the problem. And, um, *sigh* I'm just thinking about the, you know, a lot of this at the end the day—you kind of gotta go with your gut. And, uh, um…you, you, you learn quickly who's got good opinions and who doesn't. Um, and that's a skill that's not really necessarily…I mean, it…if I take it back to a university level, it's kind of, um…you know you have your good professors and your not-so-good professors. And at some point you come to an understanding that, you know, I go to that person for advice and I'm going to get good advice, I'm not going to go to that one. It's, it's kind of that…um…it's the softer skills that we engineers sometimes ain't very good at, or come to late in life. Um, because it's not as simple as: I've got a problem, I put in some inputs and I come out with an answer. Um, is that…am I…am I kind of getting to where you want to go to, or am I off on a tangent here?

[Interviewer]: So, I, I, see some good pieces to this. Something I'm…would be interested in is if you could kind of at a more technical level for me clarify what exactly you mean when you're talking about…well how do you develop these models for well homogeneity or heterogeneity?

[Expert]: Yeah, so I've got a well—and we'll just talk about the oil-bearing rock here. And, and typically they're, you know, a hundred to three hundred foot section, and I've got a series of well logs, and the well logs tell me what the porosity—you can't measure permeability, you can only measure porosity and you can measure resistance, which tells you fluid type. You can actually get fluid samples in some cases. And I can, um, with the, um, um there's electrical resistivity and there's some nuclear tools, and

between them I can tell on a log what's shale and what's sand. And I can tell what's high porosity sand and what's low porosity sand. And so, I can build this layered model in my well. And I got another well a mile away that I have the same model. Can I correlated them? Does it correlate—do…are those sand lenses stretching across the entire body? Um, and then, those…so when I…when I build this model, um, I'm basically building a number of vertical cells in model and then a grid pattern over the…over the…if you're looking down at it…over the…over the reservoir. The…how you connect these cells, or how you allow these cells to connect of course determines the fluid flow in the thing, which is ultimately what you're trying to get to. We use, um, I mean, in, in a lot of this was done in deep-water environments. In deep-water environments you're dealing with turbidites in terms of rocks, so it's not, um, near the shelf edge, um, you know where the river enters the water. So, the Mississippi River comes down and dumps into the Gulf of Mexico, the stuff in shallow water is all deltaics. It's basically a river dominated system and the sand comes down the river. It dumps it out, as soon as the velocity goes down the sand drops out and you just building over time. Um, that's the…that's the shallow water. In deep water what happens is you eventually build up a cliff of sand where you go off into deep, where you drop into deep water, and you basically have a land slide. And so you get these big bands—and how do you model that? Well you go—and unfortunately I'm not a geologist, but the geologists get to go to interesting places like the Pyrenees and the Alps and places like that—where you can actually see a turbidite thrust up on a mountain some place, and now I can look at it, and I can actually go empirically measure, um, what these lens…what these sand lenses do, and do they extend over time, over space…and how connected are they? And so you take a real physical model, and you bring it back to your, um, and, and, but you can, um, I mean there's three basic kinds of systems. The two big ones are channels and fans. And if you're in the fan, you have a large laterally expansive sand. If you're in a channel, you literally might be a hundred yards wide—really nice, thick sand body, looks great, but it doesn't communicate with anything. And so you gotta figure out which of those you're in. And at the heart of that, that's the technical problem—what environment am I actually in, and do they connect when you build these models? And so, part of it is experience, and people knowing. I mean, a lot of this ultimately is what I'll call critical thinking skills, in the sense that I have a known thing that I've done in my past somewhere or seen somewhere before, and can I extrapolate that into the present. That, at the heart of it, that's what a lot of this is. So you're trying to get people that um, I mean a simple contrast I'll make. There are two kinds of oil companies in the world, there's the national companies—the [Company 2] and the [Company 3] in Mexico—and there's the [Company 1]s and the [Company 4] and on down the list. One of the big fundamental differences between those two companies is—if you're working deep water for [Company 3] in Mexico, the only thing you've seen as a geologist is rock in Mexico, because they don't work anywhere outside of Mexico. So, all of your analogs are in Mexico. If I'm working for [Company 1], and I'm drilling a deep water well in the Gulf of Mexico, I've got Borneo, Malaysia, um, west coast of Africa, Brazil…I've got analogs all over the world. And so part of this is just bringing that to bare to the problem, and knowing how to bring that to bare. And I realize that I'm…what I'm describing here isn't necessarily a highly technical—it is a technical problem fundamentally at the end of the day—but a lot of solving it has nothing to do with the technical part, it has to do with getting the right, uh, set of eyes on the problem. And, and, and, and it's not a personal thing—it can't be a personal thing—there's just too big a world, if you will, to solve it personally.

[Interviewer]: So you're talking about this kind of from a management perspective.

[Expert]: Yes.

[Interviewer]: Where…so how do you…how did you kind of learn to decide which people were able to make these analogies better than others?

[Expert]: The…it…*sigh*…well there's two sides to that equation. Part of it is developing the individuals, so you want to put people on these teams that have…in some cases seen something like it—but not it—before, so that they get an experience that they can use again in the future. And at, at the same time, you want to put a…people on these teams that have seen something like it before. So there's tutors and…sorry there's mentors and tutors…and people that need to be tutored, if you will, both on the team at the same time. Um, it is an experiential thing at the end of the day. Um, it's not something you come out of school necessarily within a textbook. I mean all the, um, I mean if you walked over to the Petroleum engineering department there at [place], there are lots of people that build these models and can do the math and, and, the basic construction of the model and the formulas and the math itself…is relatively known stuff. It's, it's the input to that model that matters. And the, and the question that says *sigh* I mean the question you're constantly asking is: how could this model be wrong? And, I mean I use a stupid example in my class that I teach. And it's, I, instead of a geologic model I use a map of a college campus. And I put a hole in the ground and it's in the Arts Quad, right? And, and, you know there's a statue here. And now I think I know I'm where I'm…I think I'm at [Institution 1]. So, I go drill a well and, in this case, I drill a well over [Building Name]. And sure enough, the building is there, and everything's good. And so, okay, where do I go next? And I go a little farther east and I drill a well in [the lake], and sure enough there's water there. And the Ag Quad tests out, and you're doing this, but the question you keep coming back to is: how do I make this model fail? Now, I don't want to make it work. So, I go drill a well on west campus, and damned if there's not a football stadium there. And you go, "Okay, oops," and I'm actually using a map of [Institution 2]—similar campuses with buildings and lakes in the same place, except on the west side of campus there's a football field instead of….Um, so it's that kind of thought process that you're into. And it's how…how do I…how…*sigh*…the trap we get caught in is supporting the thesis we believe—if you will. The hypothesis…I got a hypothesis and I get into the trap of I keep moving forward on it that the hypothesis is correct. Where unfortunately, I think, in science, many, many things are proven by the negative, not by the positive.

[Interviewer]: Right, so…um, can you kind of tell me about a specific instance where you sort of failed at this stage? Where you encountered difficulties or challenges when you were doing this?

[Expert]: Yeah. We were in…this is in Trinidad. And, um, we had done the development. I had a b…I was the, uh, I wasn't the project lead, I was the asset manager at the time. And I had a boss who badly wanted to go fast, and he, he was absolutely conv…engineer by background, and he wanted to go fast because he was absolutely convinced we understood the thing. And we build a model, and we drilled some wells, and we'd actually drilled a number of wells and, and what was clear was: there was a nice sand body there, um, but we were right on the edge...Trinidad the north…the northern…if you actually look at the island of Trinidad itself there's a mountain range on the north side of the island. That mountain range is because you're basically at the boundary of the…of the South Am[Interviewer]an plate and the Caribbean plate. And there's um, it's earthquake prone, and that boundary goes east-west there, and we were basically, oh, 20 miles south of that boundary where this field was off shore. And, um, what we found out later on was: Yes, the sand body was relatively uniform in thickness and character, where every time you drilled the well, the, the hundred feet of pay or so look the same on a log, but what we didn't see—and couldn't image on the seismic—was, it was busted up to beat the band. There were faults everywhere. So I—instead of having a nice uniform sand lens across this field—I have here, this one was over here, and the next one's down here and they're just…and, and, unfortunately these faults were sealing. And sometimes the seal, sometimes they don't. And in this case the faults were sealing, so, uh, a 20 well development program turned into a 45 well development program. And, of course, that comes with a bunch of costs, and ultimately the field was successful but

not, not the way we though. And if we just slowed down for a little bit and tested that theory once or twice—and it would have been fairly simple to test the, the um—but we didn't do it.

[Interviewer]: I see. So how did you ultimately discover that it had all these faults then?

[Expert]: Well you…two pieces of data: one, I mean, typically, I'm trying to remember in that case, we had four, you know the exploratory well and then three or four more appraisal wells. So you had four or five penetrations when you made the decisions. By the time we drilled 20 wells and put the facility out there and turned it on, now you get pressure response data. And, and what was happening is as soon as we'd turn a well on, the, the pressures would just crater.

[Interviewer]: Mmm.

[Expert]: And the only way that that happens if you're in a confined box—a box that's a hell of a lot smaller than you think it is. And unfortunately you don't…in the onshore environment, I can back up some tanks, and, and put a temporary facility there and turn the well on and do a flow test relatively easily. And I can test that in the on shore environment, but in the off-shore environment, the rig, well in this particular case the rig was probably only a, a total spread of maybe $150,000-$200,000 a day, which is cheap. In the deep water that can be $1 million a day, and you have the problem of putting a temporary facility on something out in the water, and there's a whole bunch of safety…environmental and safety constraints. Because there's no place to put a tank and store the stuff. So, you either have to flare it—which in some places you can flare oil for 12 hours or so, as long as you're burning it—but even that we don't like to do. So, you know, doing a test off-shore is a very different thing than doing a test on shore. So often you don't get that piece of data until after you develop it. And that was the case here. We just didn't…if we had that piece of data we'd have done something fundamentally different.

[Interviewer]: I see. Um, so, one thing I'm interested in is, um, is there…are there instances that you can think of where you're working on a problem and you have to kind of go and seek out knowledge that you just didn't have, um, at the time? And…sort of like, when a…sometimes in research you encounter a problem and you have to go do a literature review, for example, because it's just…

[Expert]: Sure.

[Interviewer]: something you don't specifically know. Something you haven't encountered in your work before, or didn't learn in school.

[Expert]: Oh we'd, look, we had those problems all…I mean the quickest place for me to go here is deep water. And, and we didn't, um, I mean everything from the…the broad spectrum, I'll call it flow assurance—which is how do I ensure that my fluid that's at reservoir temperature, so, you know 200 degrees Fahrenheit, something at reservoir conditions, how do I get that vertically up a 20000 foot well and then hit the…and hit the 6000 or 7000 feet of water, you're below free...you're, you're at 30 degrees water temperature when you hit the surface…when you hit the sea floor. And then you've got to flow that back up and you've got the whole hydraulic system all the way back. So, paraffins solidify, you've got to worry about hydrates, if you've got methane in the system and the whole thing freezing up. And as long as it's flowing and you have warm fluid in the system, you're okay. But what we found was there was…I mean there's almost no data out there for multiphase fluids in these kind of environments, and, and there was a lot of basic work that had to be done. Um, on the Civil side of things the whole, um, you…I've got a floating structure at the sea floor, er…at the surface, and I'm tying it to something at the sea floor—how do I do that? Now some of that was relatively known but you're, you

basically have two kinds of structures at the surface. You either have a structure that resists vertical motion—so it's got a fixed connection to the sea floor, so there's no vertical motion—or you just let it move with the waves. The, the, what you get into is the Takoma-Narrows bridge if you get in between those two scenarios. And you get into harmonic frequencies. And, and, uh, again a lot of work around that. Now, my, my experience isn't on the civil side of it, it's on the flow assurance side as a chemical engineer. Um, but there was a lot of lab work that we ended up having to do to test…um it's really the transient conditions that bite you. Um, as long as the well is flowing—and a lot of these wells, I mean, typically we were looking for nothing that produced less than about 5000 barrels per day from a single well, many of these wells made as many as 30,000 barrels a day, so multiply that by 42 to get the gallons—but, um, large volume of fluids. And because it's coming from the reservoir and it's hot, you're fine as long as you're flowing. It's when you have an emergency shutdown condition, um, where a valve…where something forces a shutdown in the system or the facility at the surface goes down for some reason, and you shut all the wells in. And it's not planned. If it's planned, one of the things we did to engineer around this is—if the well head was on the sea floor and you had pipelines back to the surface. The, you could shut the well in at the sea floor, and we would usually have two lines that went back to the surface, and all the wells were connected in a loop, so that you could basically pump something from the surface down around the loop. And if it was a gassy system and you were worried about hydrates, you could pump methanol from the surface and, and solve the problem that way. Um, if it was, you could pump clean oil in an oil system from the surface so you could avoid the paraffin problems, um, asphaltenes was another one. So there are ways in a planned shutdown that you could do all that. But in an unplanned shutdown you just shut this thing down and now I've got this fluid, and it's changing temperature and pressure very quickly, and there's not much I can do about it. And so, there were two questions: what's the time horizon I've got to fix the problem, and what's the actual problem I'm trying to fix? And in different scenarios you had different, you know, de-pressuring was a different scenario than lowering the temperatures. Temperature was typically a paraffin problem, de-pressuring was typically a hydrate problem. And then once you get these damn plugs, how do you get rid of them?

[Interviewer]: Hmmm.

[Expert]: So there were a lot of, and I think that gets to the kind of thing you were talking about. And we used to have a joke in deep-water, was, how do…how do I build one of these things and avoid serial number one a hundred times? And because…the…in...you know…in the…I'm trying to think. In 19….in 86 was, well, 79 was the first deep water platform—we didn't actually know it was deep water geology at the time—it was in about 1000 feet of water, but the rock was in deep water turbidites. We didn't realize that at the time, but in 89…80…kinda 83 timeframe where the first deep water well is drilled in the Gulf of Mexico, which discovered oil, and then you had to figure out how to develop it…88, 89 were the first platforms that went out there, and [Company 1] did most of that. And Conoco did a little bit. And, uh, so there were all kinds of issues around, how do I do this, and how do I minimize my risk? And one of the ways we minimized the risk in the early days was, [Company 1] specialized in these TLPs—tension-like platforms—and the TLP resists vertical motion, so you've got steel tendons connecting this floating object to the sea floor so it doesn't move vertically. And, if you think about it, a wave pushes it to the side, it, it buoyancy force basically returns it to center—and they don't move as much as you think they do. But the advantage of that particular facility was that I could put the well at the surface—at the platform. And I could see it, I could touch it, I could mitigate all these flow problems. The problem with that solution is my wells have to be drilled from the platform. And I can probably only reach maybe a 10,000 foot circle around the platform. Now, the reservoirs were bigger than that. And how do I solve that problem, and the answer is you put the well head at the sea floor and flow the well back up. But,

then you have, um, that creates all these flow assurance problems. So, the early solution was to avoid it, the later solution was how do we mitigate it. And a lot of work was done obviously in between to figure that problem out.

[Interviewer]: So can you tell me about some of the specific tests and experiments you'd do to think about these flow assurance problems?

[Expert]: Sure, so uh I mean the simplest way is you could build…you could build loops in a lab. I mean, we had a number of labs in, and some of them were down at, you know, we effectively would subcontract them out to universities that could do them as well. But, universities could do the small-scale stuff typically. When you built a big model—if I wanted to do fluid flow in a 6 inch pipe—you got beyond what the universities could do. But, and then, and then there's, um…it's the structure of the industry. So, the, the [Company 1]s of the world manage the fields. They, usually, in most cases do none of the actual work. So the Schlumberger's and the Haliburton's and the number of kind of other players actually physically own the equipment and the drilling rigs and all that stuff. And, and actually do the work. So those outfits often had—I mean [Company 5] in particular has a big facility south of Houston here, and they had what we called the dynamic facility that allowed you to do some of these tests. So you could, you basically had a big pipe-in-pipe model and you could manipulate the criteria. You could manipulate the pressure obviously, you could, you could create the fluid flow in the inner pipe. Um, you could de-pressurize it, those kind of things, and then you could control the temperature on the outside of the pipe. And we just literally did it with live oil. And, uh, or, or, actually when I say live oil—we didn't have fluid samples. What we…the fluid samples that you can take when you drill a well is on the order of gallons. And basically you'd run a thing down on a piece of wire, and it's got a thing that pushes up against the rock face, and you got a little valve that opens and you extract some fluid. Um, sometimes you can collect it under pressure, sometimes you can't collect it under pressure—it de-pressurizes when you bring it to surface. The best samples are obviously the ones that are still at pressure when you get 'em to surface because you don't have to do recombination. But you're dealing with a gallon-sized sample. You know, I think I know the bubble point, I think I know the asphaltene concentration, the paraffins, all that. Kind of, I can look, I can look at an assay and figure out what the fluid actually is, and how much gas is in it. So you do recombinations of those fluids in order to run the test. You, you synthetically create the crude in question—if you will. And that, it's not perfect, but it's a pretty good simulation. And then, then you run lots of tests. How long do I have when I…given a temperature gradient of X, um, how long do I have before these paraffins start dropping out on me. And, and uh how bad is it? And the other part of the problem is—if they do drop out, if I get a paraffin plug like this—how do I get rid of it? And again you test that. Or you try to build a model at the surface that allows you to test it.

[Interviewer]: Yeah, so I'm interested: how do you get rid of a paraffin plug if it…if you, you know…if you don't have enough…if you…

[Expert]: Unfortunately there's…hydrates you can deal with. But paraffin plugs, about the only way to do it is with a PIG, you know, basically pushing the plug down the line. And that requires a whole bunch of things in itself. Because now I need a plug that can adapt to different pipe sizes to get it there, or I have to be very careful about pipe sizes to get it there—mechanically.

[Interviewer]: Interesting. Let's see, um, so one thing I'd be interested in asking you is if you could comment on, um, particular difficulties you notice, um, in problem-solving in people that you've trained later on.

[Expert]: Sure. Um, the…*sigh* well I'll give you the bias story second. Um, the…the, uh, uh because it's an age thing. But um, the, the big…well, I mean they're all biases in a way. The, one of the difficulties is people get it stuck in their head that they know the answer to the problem. And, and that's probably the biggest impediment I can think of. They think they understand the model, they think they understand the problem, and, um, and you know, and I see this, frankly, all the time in lots of other things as well. You know, someone will make a statement, and people run with it like it's the truth. As opposed to, you know, questioning it—does this actually make sense? I mean the one [Name] and I talk about it is the whole anti-vaccine thing.

[Interviewer]: *Chuckles*

[Expert]: You know it's a classic case of what I'm talking about. Very educated people can believe something that's completely BS. And, I think it was one of the books [Name] once gave me about the…somebody from, uh, how the brain worked perspective said, "sometimes in the face of evidence—contrary evidence—that proves that you're wrong, they believe it even more strongly." And, that, that really is a problem in the kind of environment that I'm talking about here. So you want people with an open mind, you want people that challenge. The worst thing from a management perspective here is you create a culture where they say yes.

[Interviewer]: Mm.

[Expert]: Uh, you know where they just nod their head up and down and go with you. Uh, you really want people to challenge. So getting that skill early is important. And I think, you know, as I think about my teaching experience now—and it's hard. Getting people, getting students to challenge you in the classroom, and you know, because and I remember when I was in the classroom—that was God standing in front of the room, I don't want to mess with him. And I think as you get father along you realize they're smart people, but so are you and they become your peer at some point as opposed to your…you being in a subordinate relationship with the individual. But how do you promote those skills really early in kind of the university experience, because I think that's where…and, and then you get into a whole introvert/extrovert, shy/willing-to-challenge, all those kind of issues. But that's part of the education I think you kind of gotta get at the end of the day—that curiosity and the challenge piece. The example I was going to give you is the, um, I date myself here. Uh, my freshman year at [Institution 1] we had to use slide-rules. Calculators were still too damned expensive, we still had to use a slide rule. And, and it's a bit of a silly example, but one of the things I saw through time is, well, when it got really easy to build these big, complex models—because they're big complex models—it's easy to believe what goes out. But garbage in creates garbage out at the end of the day. And one of the skills that a slide rule forced upon you—and I'm sure there are other ways to get it—is, you had to carry the decimal place in your head. So, if I got an answer of 10 but it should have been 100, I knew intuitively the answer was wrong. And because I…you were required, effectively, to think through the problem. And I worry a little bit that people are, because of all these advanced tools, kind of, why do you teach the derivation of something rather than just show them the equation and let them plug in numbers. It's how to get people through that thought process, that it allows them to intuit the answer as opposed to just plug in a bunch of numbers and get an answer. And I think that's a skill that we really, I mean I had debates with people about that one in the sense that, why would I need to know that as long as I put in the right stuff, I get out the right answer. Yeah, that's kind of right but there's an intuition there and, and uh, or, the question is how do you create the skill to challenge the wrong…to challenge the viability if you will of the answer.

[Interviewer]: Mmm.

[Expert]: And that's an important one for me. And that, and I, you know, most of the, I mean this may be a mundane example, but I…we do, it's two weeks. Class every day, four nighttime sessions with problems and a prelim at the end, and all for one credit. And, uh, um, I think it was the second or the third time I did the thing—there was nothing on the prelim we hadn't talked about. It was in my notes someplace, the only thing I did was I moved stuff laterally from the specific example in the notes to some, um, you had to be able to extrapolate from what you'd seen already to the problem. And I was shocked when the average on the test was a 56, and, because I didn't think it was that hard of a test to be honest. And, and I struggled with, and of course, one of the problems with a two week class is you come in, you teach, and I leave. And they usually administer the prelim after I'm gone, so all I see is the results. And so I never really got to go back and see what people missed. Um, but I, my hypothesis would be, just is the skill I'm talking about—how do I move from one…you know, I've seen it in this environment, how do I answer it in this environment? Um, that, and then, how do we teach that skill?

[Interviewer]: Right, and so that's actually kind of at the core of this project is that, the skills that I'm talking to you about, we believe are the core elements of what you're…what you're describing is called transfer. So, how do people take knowledge and transfer it into a new context. And it turns out to be one of the single most difficult things to do, educationally. You can give, as a simple example, you could give students a physics problem on their homework about, you know, hanging a chandelier from the ceiling. It has two wires, you know, what's…how strong do the wires have to be? Then you can give them a problem on the exam that's, you're hanging, you know, your climbing pack from a rock face using two wires, how strong do the wires have to be? And, they…it's not necessarily guaranteed that they'll get it right…

[Expert]: Yeah. And that's exactly what I'm describing. That's exactly what I did, and, uh, and I don't know, I struggle with how you teach that.

[Interviewer]: Yeah.

[Expert]: I mean some of that is experiential and, and time—takes or requires time, I think? Um, but some of it's deeper than that. I mean it almost, I mean I think you end up getting into personality types. And it's one of those things that makes, I suspect it's one of those things that is the softer skill that, ugh, I'm going to stereotype here…separates the good test-takers from the really…the people that can be more successful later on in their careers. It's the…and what makes, or said differently, what makes the average student much better later on is the ability to not so much take the test well, but to be able to extrapolate later on.

[Interviewer]: Yeah. Um, and so we're working on ways to do that, and that's something that I'll talk about because that's, you know, it's one of those things that engineers kind of tout as their, you know, their great skills—we teach students how to do this. But it's really not true. We're not doing a great…they're learning how to do it on the job eventually, um, well you hope, if they're successful they will be. But we're not really doing anything systematic to teach it at this point.

[Expert]: Yeah. Well, it's interesting, back to your…you, you, you look for two things, and if you're a manager putting these teams together, there's two things you…the screening and, you're dealing with internal candidates, so you're not looking at a resume per se. But the questions that you want to talk to that person about, I find the most valuable are two things: what have you failed at—because we learn a hell of a lot more from our failures than our successes—and how they adapt to that failure. What did

you do after that? And then the second is kind of, you know, the person that comes to the thing with a broader set of experiences, you know, has a better chance…often, you know, if you just look at somebody's resume, they're going to put all the things they did great on. Well, that's great. If there's not a kind of common theme that runs through that, if they're all separated experiences and they, you know, they did…it's, you know, how did I lever this thing I did two years ago to something I'm doing today. If they can answer that kind of questions, you're getting into this transfer thing you're talking about I think.

[Interviewer]: Right.

[Expert]: And if you can test that and test failure, and how they deal with failure, you have a higher chance of having a good player on your hand.

[Interviewer]: Yeah. So, one last thing that I should make sure to clarify is: so, when you've been talking about models, I sort of assumed that you're talking about mathematical models of physical thing, but that's right?

[Expert]: Yeah, yeah simulations. I mean, ultimately what you're trying to do is gather a bunch of data and then build a physical…in the on shore environment you can kind of drill your way through the thing. I mean, if you look at the shales for instance, there are very few people building reservoir simulations of shales. First of all, we don't complete understand the physics of it, because it's not fluid flow in porous rock.

[Interviewer]: Mmm.

[Expert]: Start there—it's a completely different fluid flow mechanism. But, um it's less important because the wells are cheap and I'm putting them close together, and I can kind of drill and test my way through this problem. Which is, frankly, why engineers like the shales as opposed to deep water. Because the deep water's got much larger uncertainty, you drill far fewer wells, and I'm not going to build $5-10 billion building this facility and drilling out the wells without a reservoir model. And the reservoir model is a num[Interviewer] model. It, you know, more…and in the old days we basically built a model that, um, took the fluid flow to the well at the, at the, at the sea floor if you will. Basically at the reservoir, and you calculated rates there. Now you can tie these models back to the whole system and model the fluid flow all the way back to the surface. But, um, it's that, it's that blending of that reservoir uncertainty with the mathematical model. I mean, you're building a deterministic facility at the surface. It's got a name plate capacity, you know 100,000 barrels a day. And it's designed for a certain amount of water and a certain amount of gas. That's all relatively fixed compared to the uncertainty in the subsurface. And so that model is the means to test all that.

[Interviewer]: Okay. Alright, perfect. Um, yeah. So, thanks so much for talking to me. This has been really useful.

[Expert]: Sure, it's fun.

[Interviewer]: Yeah, um, alright.

Physics (experimental) faculty 1

[Interviewer]: So we're interviewing you, you as part a the project to sort of identify how experts think as they solve different complex problems in their work. And the goal is ultimately to identify what students should be doing in order to improve their own problem solving, so that we can figure out ways to teach it.

So today I'm going to ask you about a problem that you've solved or a recent project you've completed and asked you to the walk me through all of the detailed steps, with particular emphasis on the detailed decisions that you made as you were going through and solving the problem.

Um, So to start, just think about a problem that you solved in your work or a project you've recently worked on. And then, can you walk me through the goals of the project, what did you do step by step.

[Expert]: Ok. So what kind of…we solve problems that are kind of a very different scope all the time. So there's like entire research projects that will be published versus…we had to fix something in the lab versus building a new instrument versus…so what scale do you want?

[Interviewer]: Um, so whichever scale you feel is appropriate for me that was sort of like a sufficiently challenging problem for you.

[Expert]: Okay. Give me a second, to think of the best possible one. [long pause] So do you want like some scientific background technical detail…what, what level?

[Interviewer]: I don't need too much technical detail. So it's okay if that goes over my head as long as you give me a detailed account of what you were deciding as you went along the way.

[Expert]: Yeah. OK. So the project itself is, um, you've heard about quantum computers?

[Interviewer]: Mhm.

[Expert]: So, We don't have on computers yet. And one of the ways to get them is to find something called a topological superconductor. And if you could find a topological—and I'll explain what I mean by that—if you could find a topological superconductor, you could use it to build a much better quantum computer than any of the current implementations. This is broadly known to be true.

But basically you need to find the right type of system to do it with and that system doesn't exist yet. Microsoft's spending billions of dollars to try and do this, but digress…not a quantum computer person but I study superconductors. So there's a well-defined question…So there's…superconductors are either topological or they're not topological and topological is like…means, there's some global property of the system that is…well let me give you an example.

A nontrivial loop of paper is [makes loop out of paper towel] Take a loop of paper and that's a non…topologically nontrivial loop of paper. [Reforms paper] That's a Moebius strip. That's a topological non trivial piece of paper. Um the example, that's usually given is like…an orange is a topologically trivial surface, it's a just a sphere. But a doughnut has a whole in it, and a whole is a nontrivial thing. So in a very abstract sense superconductors which are things that have zero resistance at zero…resistance at some low temperature…they can have a topological aspect to them which the technical details are really confusing, but it doesn't matter. They have some global property. And it's the fact that that that is

topological. It's like a twist in their electronic properties and that twist means you can use that twist to do quantum competitions.

In a very robust sense because the, the thing about a Mobius strip is…if I…focus, like I stretch it or I squish it or I do this. Good. It's still a Mobius a strip. Right? Or if I take a donut. I can form it, it's still a donut. It still has one hole. The thing you want to care about is number of holes. Its robust to me poking it. Whereas the other ways to do quantum computation are not robust, which means interference from the outside world completely screws them up. So, but that's the big picture goal. People want to topological superconductor.

Fine. So there's a material called strontium ruthenate…strontium ruthenium oxide and this is a material that people grow in a chemistry lab somewhere, and it has some evidence that it could be a topological superconductor and some evidence that it might not be a topological superconductor. And what we set out to do was to design a new type of experiment that could…wouldn't answer…so superconductors have lots of different properties and different measurements tell you different subsets of all these properties…we wanted something that didn't tell us really anything about all the details, it could just say topological or not topological at all the experiment was going to do.

And I didn't invent this idea. It's been known in the literature for a very long time, that if you measured actually the sound velocity in the superconductor as a function of temperature. When you measure…so just literally the speed of sound, how fast the sound move…you know sound moves through air, it moves through metals, it moves through water. If you measure how fast the sound goes through this thing as a function of temperature when it becomes superconducting, so when you cool it below 1.5 degrees above absolute zero, it becomes a superconductor. If the sound velocity changes in a particular way…Because when things become superconductors, everything changes, including the speed of sound, including the reflectivity, including…it's not just the resistance.

If it changes in a particular way, then we know it must be a topological superconductor. If it changes in another way, it must not be a topological superconductor. And the reason this experiment had never been done was because, uh, in air, there's only one speed of sound. It's whatever 333 meters per second. I solids there's more because they're…they're single crystal materials and the sound is different this way, than that way and compression is different than a shear and there's six speeds of sound. And there was the…You basically have to do six experiments and compare them in very detailed ways and there's too much systematic error in my opinion, that was so my, my first, there's kind of two main ways to measure sound, one of which is the one that everybody does all the time called pulse echo. And that way you have to do six experiments and I knew that the systematics there were just overwhelming. People have tried it before and they could never say anything because you need to compare six… you take six big numbers and subtract them and look at all the differences right…any uncertainty just gets blown up.

So I learned during my postdoc at different way to measure the speed of sound, where you can do it all at once you just do one measurement you get six different numbers. And so the first experiment that I had my first student do was to build an apparatus to try and do this experiment. And there were a number of constraints on what we needed: one, we needed…this thing had to get very cold. It's 1.5 degrees above absolute zero is where the superconductivity happens. And it turns out for technical reasons, it's actually very hard to measure the speed of sound that cold because when you put sound does something, it gets hot…uh, sound energy dissipates. And it gets hot. So I…we had him. We had a…we basically this is kind of the first…Well, I wanted to do it this particular way that had lower

systematic uncertainty. And so…there were so many unknowns in how to build this experiment, but what I did was say, Let's just, let's just basically copy what I did during my postdoc, let's just build that thing. And I know it's not quite going to work. I didn't really tell it to him like that but I…I said it's not quite going to work, but it's going to at least get us close and we'll, we'll know how to improve it from there. If we try and just build the perfect experiment brand from scratch, I won't get tenure. It will be will be, you know, five years before we even start to take our first data and then, you know, we may have missed something obvious and then we'll know nothing. Right. So we built…we had to build a low temperature that it's…it's ultrasound that we use to measure the sound, which means it's, it's up in the megahertz frequency range. So you need to send the sound pulses first as electricity through coaxial cable. So, Coax, which people use in the lab and that when it gets down to where your experiment is at one and a half Kelvin you have a transducer, a little bit of piezoelectric that turns that electricity into sound and then that sound goes into your sample of strontium ruthenate. It comes back and then you measure things.

So there were a lot of technical problems that we didn't know how to solve like we, we want to get sound down through coax but coax is known to…it's copper metal and it brings a lot of heat down from room temperature because metal conducts heat. So I said, let's just build something. So we just build something. And it turns out we couldn't get cold enough stopping it around two Kelvin or so, basically because all our coaxial cable was bringing heat down from room temperature and I knew this was going to be a problem. But it was a brand new experimental system. I didn't know how exactly we would solve it here. So we built it, didn't work. Student took it out and we rebuilt the way we attach the coax in various places and we solved that problem. So we have to solve kind of the thermal problem of trying to get the experiment cold. That took, I don't know, four or five months because the student started off with essentially no knowledge of anything. Right? Nothing, no experimental skills coming into grad school, basically, you don't know how to do low temperature physics. You might have taken a lab course but of course it's not teaching anything. So we work one on one. And we were in the lab, kind of, all day, every day, teaching him how to solder things, cut things, go into the machine shop and build little parts of the metal…because you can't buy this apparatus. There's no like vendor that sells you this experiment.

So we got that…kind of working. We put our sample in there. We cool the whole thing down and measure the sound velocities all the way down from room temperature down to 1.6 Kelvin. Which that's thing we're using that's as cold as it would go. And the magic number, though, is 1.5 Kelvin. So that…that was pretty frustrating that we couldn't get it any colder than that. So at that point, we had an idea you so first. Now, we knew we could measure sound velocity down to very low…300 to 1.6 and 300 to 1.5 that different. So basically you've solved…most of the problem is getting cool but this particular cryostat wasn't going to cut it. So we had to, um, basically start from scratch as far as the apparatus was concerned. And so we went and talk to…and [Institution 1] is one of the most famous places in the world for low temperature physics. And so there's, you know, people who did the PhDs here in the 70s, who know this stuff have written literally written textbooks on it and so…We went and talked to…this is [Name] and basically he worked with [Name], who won the Nobel Prize for Helium 3. So we talked to [Name] and he helped us design a completely new experiment and really it was finding an expert like that. Because I can't be an expert at everything and acknowledging that is one of the hard things physicist have to overcome, which is, you know, I have to know about the idea of what to do I have to know about the sound velocity type stuff. I have to know about how to prepare the sample…There's a whole pile of theoretical stuff, which I haven't even got into that we have to know about to know how to do our experiment properly. There's a bunch of electronics. There's data analysis. I can't be the

world's best all those things. So we went and talked to [Interviewer] Smith to help us design the low temperature part of this experiment.

And that took half a year to design and build and implement. Um, it involved, the whole bunch of vacuum cans. It doesn't matter what the details are. And we cooled that down sometime last spring, and we were actually able to get below down to 1.2 Kelvin so 1.5 is the magic number. Um, and so…one of the interesting things is…so my student initially took some data. And I was, I think I was away on travel and he kind of started analyzing and stuff like this. And I think one of the, one of the things that comes from just experience in physics is knowing when your data is even worth analyzing or when you should go back and take better data.

Um, I'm drawing pictures. Probably not very helpful but at least for you…it won't be on the video. Measuring the sound velocity as a function of temperature here. And he saw something that kind of looked like this. And here there's actually six speeds of sound Some of them do this and some of them did that. So there's six numbers there. We started analyzing it. And when I got back, we had to sit down and really think about…What should this actually look like? Because you know I measured sound velocities in lots of other superconductors…not topological ones. Um…we know from a measurement of, say, the resistance of this material as a function of temperature that the resistance should look like that. And this width here [points to logistic curve], should be about 0.05 Kelvin. What he was looking at was more like 0.5 or more. And so I knew at that point that while the physics we were looking … and what that sound velocity should look like….is it should be a sharp drop I don't…phase transition into the superconducting state, just like the resistance. And so I knew that while the physics we wanted was there somewhere. It was smeared out due to some kind of experimental problem still. And so that's something that student didn't appreciate, because they don't have all this context of, you know, what should the measurement look like…you kind of have to know the answer in physics before you do something. Say like you're doing theoretical physics. If you just calculate things and you don't know what you're looking for, you can get anything you want. You don't know if it's the right answer. [Physicist 3] will tell you more about this.

So we had to redesign a couple more things. And eventually we got some data that actually [draws] look like this, and a couple of them had nice drops and a couple of them didn't have any drop. And it turns out though right combination of them had the right number of drops to tell us that this is a topological superconductor. Actually, this is what's called a p-wave superconductor. But then, so fine we have that. Now, how do we build that into a convincing story, right? Because that on its own convinces people who do ultrasound for a living, because they know the details. So right now we have to turn this into a manuscript that's…it's a, it's a big result. This is an important result in the field of low temperature superconductors and quantum computer…all this kind of stuff. But if you…so if you want to write it for a journal like Nature, Nature physics or science or something like this, you can't just start talking about sound velocities and things like this because, even in my field, nobody does this technique anymore, right? This is an old fashioned technique kind of up...we've updated a bunch of electronics and did some new things, but it's not something that anybody reading one of those journals is going to be familiar with at all. And that of course is probably the hardest thing for a student is to understand how to put their results in a context that a broad audience can understand.

And so, first, what we had to do is we had to go back into the literature and find other examples of where people have solved similar problems using sound velocities that we…at least we can cite papers that are published that people, you know, gives people a little bit of confidence that hey, okay, sound velocity is a thing that can actually measure, um, these types of properties. Then we had to…do a bunch

of theoretical work basically it's some group theory analysis. Um, there were five papers out there sort of predicting this effect for a topological superconductor. And they had four different answers. Only one can be right. This is a deterministic thing. So it turns out there were four different ways you can make a mistake. And we…and actually all four of them are wrong and different…all five of them were wrong in some different ways. But then, of course, so we have our own answer for what…it comes down to: which one of these things should…there's six sound speeds, which one should drop and which one should stay constant? Um, and there were disagreements about which should do what. And of course, we got our own answer. And then the question is, you know, five other people made mistakes. How do we know that we didn't make a mistake. That's always very hard to do.

I mean, the first step is realizing that you can't just trust what's in the literature, even if it's published . You…you have to actually check things yourself. And then the second thing is fine, you check it, you get your own answer. How do you know that what you're doing is not total nonsense? So we developed a couple…we looked into some what we would call consistency checks. Um, there's actually…it gets into thermodynamics and something called Ehrenfest relations, but these signatures should be in the six sound speeds should actually be relatable to each other in different ways, in a way that had never really been looked at. And so we checked those relations and they showed us that, yes, our answer probably was correct, because the numbers actually related to each other in a sensible way. Once you invoke thermodynamic laws you, there's no dancing around right? Thermodynamic laws work, so you don't get to goof around with the first law of thermodynamics. But then at that point we contacted a couple of the authors of the other papers and said, hey, I think you made some mistakes. Would you agree with our new analysis? They did agree. So that's not a proof of anything either. But at least gives us more confidence that what we thought we had identified as a mistake was, in fact, a mistake.

So then we have kind of a theoretical framing for our result, which you need, you know, because even without that theory I still had some intuition for why this was the right experiment to do and why seeing a jump in a certain sound speed would tell it's topological. But that's not convincing to anybody except for me. So this is where we had, and you know you might think you would work out the theory first and predict and then go measure, but that's completely useless because there's five different theory papers out there that are…all have a different answer and it's not just solving polynomials. There's…these are hard problems and you have to make decisions at certain points of what terms of to drop and what terms to keep that are based on physics. There's no mathematically rigorous solution to many interesting problems in physics. So you have to decide what…what to keep and what to throw out. So if you try and just predict what the effect is going to be without doing any kind of a measurement you…it's it's…kind of the wrong order for a lot of condensed matter of physics experiments. Most of what people do in quantum materials or condensed matter physics is: you do a measurement and then you try and fit it into a…a broader theoretical framework. And sometimes you need…somebody needs to go to invent something completely new theory and that, you know has cascading predictive effects, but it's…it's very much not the case that, um, somebody just dreams something up and makes a prediction and then somebody goes out and measures it and somebody else dreams… and so in physics in general that very, very rarely happens. Einstein is sort of an example of general relativity really wasn't needed at the time to explain anything, it just was a consequence of his own internal uncomfortableness with certain aspects of physics and it turned out to have broad consequences. But that's an extremely rare exception. The rest of theoretical physics is usually trying to understand an existing experiment. That's a little bit off-topic. But anyway, the point is we did the theoretical analysis is kind of after we had a result because there's no point in spending a ton of time doing the theoretical…what are you going to do? You're going to do the theory and might tell you, no there's no effect, but you don't even know if you did the theory right. So you may as well measure it, see if there's an effect. And then, then, then you

know the answer there is an effect. One of these sound speeds shows a drop. Okay, I know that. Now I have, it's a it's a truth. It's an experimental truth. Now I have to understand. Where could that possibly come from. Anyway, that's the approach we took with this particular problem.

Um, it's not quite so chronological it's really a mixture of doing everything all at the same time, but really we…we needed to have some kind of grasp on what the experiment was going to look like before we got into trying to understand it from some theoretical basis. Um, so the proj…that's essentially where the project is right now, we're now writing a manuscript and this is now the very iterative…this is the hardest part of science. It's a very…lots of people have tons of data that's sitting around…taking data is easy, publishing clear results is very hard, because we have to write it in a way that it's convincing and that it's accessible that it's clear that this is an important result. And we have to, you know, do…The weird thing about my area…area of physics is you'll almost never see error bars on anything. Because…so particle physics, the other half of this building…uses error bars, all the time. Because what they do is they count things. They have detectors and they count events. And so there's a very natural way to put an uncertainty…statistical uncertainty on that and they're very good at modeling their systematic uncertainties and including that. In my field of research…what's called condensed matter physics, nothing is exactly…just about nothing is exactly solvable. So everything we're doing is some very large approximation in terms of analysis. And so to put statistical error bars on what you're doing is very misleading. Because yes, I know…you know I know, let's try to measure…uh what is TC? Yes, I might, you know, I could put a little error bar on there because I didn't identify the width of the transition, but really the systematic effects are always so large and so unknown that there's no real way of…you're better off just discussing them in terms of words, rather than just trying to stick a number on there. So we have…we have a bunch of different systematic effects in our experiment. They're not…some of them are quantifiable, some of them are not quantifiable, but we need to convey to the reader that we understand them, and we have accounted for them, and that they're not responsible for our result. But it's not as easy as, you know, running some statistical tool on our result because that requires a model and there, there is no model for a lot of what we're doing.

So overall, it was a success. This is something I had hoped to do when I came to [Institution 1], it did work. We, the fact that we had to rebuild the experiment completely, rebuild it from scratch twice and then there were a lot of iterations in between on the apparatus was annoying but…expected. That's usually how things go. If you want to do something that's quite new, you will have to iterate. And we actually, as an interesting benefit, when we had that first version of the apparatus and I thought, Okay, we're going to build a whole new one, and it's going to take a year. We actually took a pause on this experiment for a little bit and we measured a different material for different reasons, uranium ruthenium disilicon, where we could ask a similar type of question, but where we kind of already knew the answer. But with using it, but asking the question with this new technique…asking something about the phase transition topological or not topological, the answer was already kind of known through different methods. Um, but we want. And the answer was, it's not topological and we wanted to confirm that our technique would actually give that answer. So the…the reason we could do it with our original apparatus is instead of 1.5 Kelvin, it was 17 Kelvin, so much easier. So we actually spent half a year doing that experiment instead. And really, that's where we ironed out a lot of the theoretical analysis was at that point. We had something where we kind of knew the answer that we could test it on. Um, we actually got involved with a machine learning project at that point that brought on and we figured out a whole new way to analyze our data that was independent of all our…it basically allows us to get rid of a lot of the systematics that I was talking about. By not having to do all this crazy analysis, we could do another approach using a machine learning algorithm. And that that was an interesting, fun diversion that actually taught us about the power of machine learning for this particular technique. And

that's actually almost published that was a successful diversion and even if that was the only outcome of the whole project, it would still considers…consider it a success. So we developed a new technique we found an important science result in this uranium ruthenium silicon two. And we'll continue to use, you know, this apparatus and this experiment and this analysis with machine learning for future experiments But we did go back to the strontium ruthenate and we did find that this one probably is actually topological…that there's some loose ends that aren't quite tied up on that, if that's under publication as well.

[Interviewer]: So how did you decide to measure the speed of sound material first place?

[Expert]: So, um a lot of experiments…um…and…looking for, uh, this is sort of philosophy, but…it's nice if you can, if you can do an experiment that relates to, um, symmetry—ideas of symmetry. I don't. Your chemists…chemical engineer?

[Interviewer]: Condensed matter theory actually.

[Expert]: You're a condensed matter theorist? Oh, so you know group theory.

[Interviewer]: You know, soft condensed matter. So yeah, we don't we don't use it much.

[Expert]: I know you don't have any symmetry in your problem. Yeah, so you're aware of the concept. Okay, so, um, what I wanted to avoid in tackling this problem was having to rely on a what we call a microscopic model of the physics. Because there's only one microscopic model for superconductivity, it's DCS theory. It's one of the most famous results in physics. It's the basis of like Higgs-Boson and all this kind of physics that came out. And DCS theory definitely does not apply to this type of superconductor. But there's a bunch of phenomenological theories, people have come up with. And based on different ideas, but we know none of them are correct. So I didn't want to have to do an experiment. What I didn't want to do is measure the magnitude of a number and have…have to compare with a theory that says the numbers should be this big if it's topological, it should be this big if it's not topological, because then…you know you can you can do that and you can write a paper, but people know the theory probably isn't right. And so it's very hard to be convincing enough. And what I wanted was something that's constrained by symmetry. So I measure six..six speeds of sound, six numbers. And if it's a certain type of superconductor then by symmetry, only three of them can do this when it goes to the transition. That's a group theory statement and group theory is Powerful, it's a yes no thing. There's no dancing around it. It's this is allowed, or this is not allowed, you know, the symmetry of your crystal lattice that's known. So, therefore, you know what's allowed what's not allowed. If it's a topological superconductor five numbers are allowed to change when you go through that phase transition. Doesn't mean they have to change it means they are allowed by symmetry, which is very powerful statement. It doesn't…doesn't have anything to do with whether it's electron-electron interactions or electron phonon interactions or what…what the microscopic mechanisms are of the superconductivity. Doesn't even actually matter that it's a superconductor, actually, it just matters…there's some yeah I won't go into all the technical details, but it's a, it's a, it's a symmetry statement of…If you see that, then it must be of this class of order parameters. It doesn't tell you all the details about the superconducting order parameter, but it tells you, it must belong to this particular class.

But that's why I wanted to do this experiment, it's one of the only experiments where you can make that sort of definitive categorical…it, it does not belong to this type of thing, it must belong to this type of thing. And the topological ones are in this type of thing. So it was the type of question I wanted to answer but there's lots of other ways to address is a topological superconductor or not. But those rely

on some kind of theory and some kind of modeling of what exactly is going on a superconducting phase. This is one that just it sort of it doesn't give as much information, but these gifts very strict symmetry based information.

[Interviewer]: Okay. What is your motivation for sort of deciding to use this ultrasound technique?

[Expert]: Well, the motivation for most of this is do anything is that's what you learned as a postdoc. But I had a suite of different types of ways to do ultrasound. And the reason I chose…which I…some I knew, some I knew I could know how to do if I wanted and this particular one is the one I chose because I knew about…it goes back to this idea. We need to compare six numbers. And if we have to do six different experiments, the systematic differences between the experiments are going to overwhelm everything. If I have to take…the other ways of measuring sound, you need to cut six different crystals align them very precisely, glue on six different transducers align those very precisely have everything lined up…thermal equilibrium, all this kind of stuff and then do your experiment six different times and compare all those numbers. That's extremely difficult to do. If you're looking…so we're looking for a part per million effect. And you've got to do it six times and not have systematic errors screw you up.

Whereas with this particular resonant ultrasound technique we could…it doesn't have…everything is a trade-off. It doesn't have some of the other power that the other techniques have but what it does have is the ability to get all six numbers at the same time. So that's really why I chose this one because I knew it could…it was a great way to eliminate a large part of the systematic error, other people had tried this experiment…not with the resonant ultrasound, but with this six different experiments technique and I don't think anything was published, but there is a PhD thesis of some people I know where he had some data that was kind of preliminary but they were never able to publish anything because it wasn't convincing. So that, that's why I chose this particular iteration of the technique was to eliminate the systematics that I knew who played other attempts to do it.

[Interviewer]: Okay, well, I'm curious as to how you certain solved the initial thermal problem with the temperature conducting down the coax cable into your sample. What, what kind of information you needed to collect and what sort of thought processes went into solving that.

[Expert]: Oh. That's a good question. Can I draw pictures still? So, the problem is, so here's room temperature 300 Kelvin. That's where your connectors already are, your coax. And then they run down into cryostat and connect to copper block that you want to be at**…**in this case was actually 0.3 Kelvin. And then you do your experiment on something attached to this metal block.

The problem is, you can calculate…you there's a thermal integral something you can look up something I've…this is problems I've run into before, these are known if you've done…done low temperature before this is known to be a problem. You're trying to balance two things. Thermal conductivity of the coaxial cable. So if you use copper. Copper is great at conducting electricity and there's something called Wiedemann-Franz law, which means if something's good at conducting electricity, it's also good at conducting heat---and it's almost impossible to beat. If something's bad at conducting electricity. It's bad at conducting heat. There's exceptions like diamond…like some, there's some insulators like diamond's incredibly good at connecting heat, doesn't conduct electricity. That's an insulator, though not a metal. Unfortunately what I needed a metal because I need to conduct electricity and I don't want to conduct heat. In this realm of metals, there's no analog really good at electricity, not heat. That's not true…superconductors, superconducting coax is a perfect solution, but for technical reasons doesn't work here at all because you have to…there's no room temperature superconductors. So it really only

works from 17 Kelvin down where we get [unintelligible]. So I'm the initial thing we actually tried…There's actually a place. So this is sitting the coax is sitting inside a stainless tube. And that stainless tube is sitting in some helium and gas that is at let's call it 2 Kelvin. The problem is it sitting inside, inside where the…the coaxial cable is to the little connector out here to the outside world. This is vacuum. So there's no thermal connection between the coax and the walls, which are sitting nicely in some gas that's at two Kelvin.

So the first thing we did was we wrapped the coax actually in copper foil at one place so that…because…So what do you want to do? You want to be able to dump your heat out. The amount of heat capacity that something at point three Kelvin, as is not…heat capacity is the amount of energy You can add to raise the temperature one degree. Things that point three Kelvin do not have very much heat capacity, you have a lot of heat to get rid of. So you'd like to dump it into something warmer. So we actually made a connection to something up at two Kelvin to dump out as much of the heat as we could Just buy wrap…soldering kind of copper braid to the outside of it so that there was a direct connection, because this had to stay vacuum so that now there's some kind of metal to metal contact. Then there's actually a connector here. And so the first thing we did was we undid that connector and we…so your experiment is it's down here. This is cold, and this is at two Kelvin around it. The first thing we did as a diagnostic thing was I got a student to put a thermometer on there before we put the braid in there. And after we put the braid in there. Before we put the braid in there, this end of this coax was at something like 100 Kelvin. Was it cools to radiation but relations T to the fourth or whatever. So once you get the low temperature, you don't really have any.

We put this braid on there and we got it to 10 Kelvin, actually. But that's a lot because the amount of heat…it's not a linear function of temperature, it's an exponential function of temperature. Then there's actually. So we tried the experiment actually still didn't work. There's another block of brass in here that actually sits a little bit colder, it's, it's at 1.5 Kelvin. And so…or 1.6 or something like that. So what we did was we actually took the coax and actually soldered it to a block of metal that was bolted into this 1.5 Kelvin and that dumps even more.

We have to you know we…I knew this is going to be a problem. But you don't want to start. I knew that it could be a problem. But you don't want to solve problems you don't have yet. So that's why we built it without doing the full thermal engineering because…the thing I haven't told you is all this stuff is sitting in a…what is a commercial variable temperature insert from Oxford instruments. And it's a new type of one where there's no liquid helium. It's all just gaseous helium and cryo compressors, whatever. And I never…they're new, so I didn't know anybody who had done all this kind of low loss low temperature coax in a dry…system with no active liquid. If there's liquid helium around you just get the coax in the liquid, and it cools. We didn't have that here. So it took a little bit of…it wasn't just me being completely naive. It was. I didn't know how much of this heat sinking type of business, we would have to do. And you don't want to go overkill right from the start, because you'll spend half a year trying to heat sink something, if it's not a problem, you're wasting your time. So that's, yeah. That's how we solved that problem. And it's been very useful for other experiments, so in the end it wasn't a waste of time.

[Interviewer]: Um, in sort of developing a way to measure these six speeds of sound…what do you think the most important parts were in this whole process?

[Expert]: So, I think the important, the most important parts were all to do with knowing where to focus our time. I think…If I had just given this project to a PhD student and kind of told them about it, you know, they also probably could have done it. But it…you would take 10 or more years because you'd

have to stumble randomly down the path of trying to solve the problem. So I knew…the part I didn't get into it all was how to prepare the sample. I knew that it was worth taking a lot of time and doing that extremely carefully basically making sure that…so crystals have an orientation. They have axes that the…the crystal was polished parallel to those. It's like a little cube of material that it was polished very carefully parallel to those axes. So before the student even got involved in any of this when he first joined the lab I had him just…polishing is something that it's actually not that easy, but it's something that somebody with no skill can learn how to do…you don't need to know any physics.

So he spent quite a bit of time working on that, learned to x ray it and really the fact that, the whole time we were doing this, we had an extremely carefully prepared sample to work with meant that when I saw things in the data or didn't see things in the data, I knew at least what we were looking at wasn't just crap. I knew what was that the sample itself was right for the experiment. It was well defined geometry is…we've done x ray on it and make sure it's clean, it's very easy to just kind of get samples of a superconductor from somebody start measuring but, from my previous experience, knowing how important it was to fully characterize the sample and make sure it was exactly suitable for the experiment, we went through quite a few different samples to get to the right one.

At that point, I knew. Okay, we can start spending our time trying to do physics. Otherwise, if you, if you, if you don't do that first and you can never get the right sample…So there's certain types of super connectors that only grow in extremely thin, like a sheet of paper almost. If we had spent all our time trying to build this experiment for a sample like that…a sample like that does not work with this technique and all that thin plate just bends. And so if we hadn't done the sample step first, there's no there's no point in doing anything. So because techniques would just never work. So first, making sure that we would be able to get a sample that's suitable for this technique. I guess in sort of a high level thing…to make sure that all the different components that had to come together were compatible. One problem with some types of experimental physics is when people have a certain apparatus…you know the expression when all you have is a hammer, everything looks like a nail. That can be a big problem. So if you only have one type of experiment that you do and people are interested in certain types of you'll just measure everything with that one experiment, but it's not always suitable. Because we were starting from scratch and we had a choice of different types of techniques to do, I wanted to make sure that the sample we were looking at was, was able to be compatible with this type of technique.

And then I think it was really important that we built the first version that ultimately was a failure, but took us off into this side…you know now published successful side project that taught us more about how to do that data analysis with machine learning. Got us really focused on solving the theoretical problem and looking into the literature for those problems. And we kind of uses it as a benchmark for the technique because we kind of knew the answer. Because this was something that was new…we wanted an already answered question that we could reproduce basically. This other material that we knew was not topological…we wanted to be able to reproduce the trivial case before we went made wild claims about the non-trivial case.

Without that…without being able to, you know, now we can when we finish writing the paper on the strontium ruthenate—the topological superconductor—we can point at our now published other results and look and in the case where it's not supposed to be topological our technique shows that it's not topological. I think that's really important. And I think…When we were taking the data itself we ended up having to goof around a lot with the amount of what's called exchange gas. Thermalizing the sample, making sure it's all in thermal equilibrium. you're trying to make some statement about thermodynamics. And that's something that's very easy to overlook. That's kind of the thing with the

student took the first set of data, it's like okay and start playing and analyzing it, it's like, whoa, hold on. You can see, with some experience, in the data that we don't know the temperature at all, the temperature is different on different sides of the sample. Part of it's hotter than the other part. So you can't say anything useful there. Sorting all that out was really painful and not fun and didn't feel like doing physics, but without that we wouldn't be able to make any meaningful statement.

[Interviewer]: Okay. So then what are the next steps for this project, this technique, this material?

[Expert]: So, for this project, I hope we have enough data that**…**this is now publishable as is. You have to kind of make a choice for what do you want to get a second sample and redo the whole thing. For certain things that's important. Given the signal to noise we have, I don't expect a second sample to look any different. Given this…all the other properties we've measured up the sample with the exact same as every other published property. Thermodynamics works. I don't expect this thing to just randomly have a different sound speed than everything else. There are actually, in addition to sound speed we measured sound attenuation, which is just how much it absorbed sound and because there's six different sound speeds there's six different sound attenuations. And, I hadn't initially appreciated that that would be useful information for this problem, it doesn't fit into the theoretical analysis that we've gone through. That…none of that describes what attenuation should do it just tells you what it's sound speed should be. It turns out surprisingly the sound attenuation, the temperature dependence of it is very interesting through the superconducting transition. Some of the attenuations go up some of them go down. Now we've started looking into the literature at what has been seen in other types of superconductors. It looks like this is even more evidence for the claim we're trying to make about the material. But that's less well…we haven't…we don't have a well-developed kind of calculation for what to expect. So that's where we're going to have to reach out to people who have worked on…theorists who have worked on this and really try and make sure that, you know I, again, I have some intuition for what I think the sound attenuation is telling me, but whether we can quantitatively say something from it. That's going to involve some collaboration and I'd like that to be part of one paper. I don't think I want two separate papers. I think that's one piece.

And then there's a lot of up. Not a lot. There are other materials that people are growing all the time that are potential topological superconductors. So now I think we can take those materials and put them in this apparatus.

[Interviewer]: Cool. Let me just think. So I think we've covered most of the things I wanted to. Um, one thing I'm curious about is what difficulties you've noticed in your students with regards to training them to the experimental physicists.

[Expert]:

I mean, the difficulty mostly lies with me and knowing…you know expert blind spots and all this kind of stuff, you know, the professor you're aware of them. But still it's actually very hard to anticipate what they will know and what they will not know. And to it's hard to recognize what did…my two best students are clearly much brighter than I am, in terms of in terms of…I wouldn't say brighter, they're more…they could solve any math problem way better than I ever, ever, ever could have. I have a kind of intuition for math, but I can't actually calculate things without Mathematica, I make mistakes. They are extremely efficient and good at it. But their idea for what's an important part of the experiment to fix and what's not an important part of the experiment to fix or what's an interesting science question to ask and what's not an interesting science question to ask…They don't know anything about. And I'm not

frustrated with that. I just that. That's the biggest challenge is when they come to you with…like a paper, they found and they say, look, isn't this interesting? You don't want to say, No, it's actually not interesting. It's probably bullshit, but…Because you don't want to just dampen all their enthusiasm, but you have to be able to convey to them, look, there's some serious problems with that experiment. It's interesting idea, or maybe it's not an interesting idea. Evaluate it critically. They have no reference point for that at all. I don't know how…Why, they, they would other than maybe…maybe undergrads should take part in a journal club or something. But I don't know if they're ready for that. Yeah, we…we…grad students, my group and two other groups. We have a journal club, we go through papers every week, which are Nature or Science…some high profile result that those papers are not…more or less correct than lower profile…in fact they're usually less correct than…the claims they're making. Science is usually, the experiments are usually good, the claims they're making aren't.

Going through that with the students is, I think, really important for me. I think they I know they get a lot out of it because they tell me to get a lot out of it to be able to discuss with the…All the levels of seniority, you know, the advanced grad students postdocs PIs, but they're all everybody's different opinion on the validity of the experiment. The validity of the analysis and interpretation, whether they're actually asking an interesting question, whether they're not. And I don't know that there's a place in undergrad to do that, but I think a journal club is the right place to build that kind of experience.

Electrical Engineering industry 2

I can think of several projects I think are kind of interesting, but anyway…

So I'll tell you about one that was ….well…after that I can talk about other ones, since I am not sure I want this taped…So around ….this wasn't that recent…around 12-13 years ago…I was still working at [company] and a bunch of people got laid off and they kept me and they said "Here, do something…your part of this new something called business creation." And they said "Do something with sensors." And I thought what the heck… so I go to a conference on sensors and I listened to a talk about image stabilization by…I don't remember….one of the big companies like Nikon or [unintelligible]. It was gyro for image stabilization. They said it works great, but too expensive. And about this time I had also worked on a different project having to do with wearable displays and we also wanted to do image stabilization with that and …we used a mouse sensor to do that. A mouse sensor…you can [scan across the page?] if you put a lens on it. It will measure angular motion as well, and so we decided to start a business doing that and so we built some prototypes of that…then for whatever reason…then Avago spun out and I lost track of what happened. But it never quite made it as a product, but it is a cheap way of making on image stabilizer. About the same, I was contacted by the mouse people to go to [place] because they wanted to make also a gyro and a pedometer kind of thing. They wanted to make a gyro for people and GPS stabilized. They wanted to make inertial guidance systems.

You know what [place] is? [Place] is a government lab…government contracts…they make…they started making inertial guidance systems for missiles and then they wanted to build one for people and GPS…what are they called…in areas where they could use radio. Tunnels or something. So they had these big things that were ring laser gyros or fiber gyros and they wanted to make something cheaper, so we helped them build a gyro with the same sensor as we built for the camera.

Q: Can you tell me more about that sensor? And how you made it?

So the sensor was invented…that's an interesting story too…it got started….did you know [Name]?...He worked in the [sub] group at [company]…and they wanted to build a paper position sensor to help…to take out banding and more precisely align the drops in the right place, but sometimes when the paper doesn't move the right distance you get banding…so they built this thing that became the mouse sensor and they took it to the business and the business unit said "Oh that's too expensive…it works great, but it needs to be less than free for us to do that." So then people started thinking about other things to do with it…and one of them was building a hand-held scanner… so what they did was they had this vision of something they take out of your pocket…imagine a pencil as the scanner...so you take it out of your pocket and it has two of these position sensors on the end and then a scan bar in the middle and the lighting system and then you can go like this [gestures] and by measuring the position of the ends you can undo all the distortion of the scan. And they call that [product name]. And that did become a product, but it didn't sell much…it morphed into something big and clumpy by the time engineering reality sunk in, and they sold it for awhile…it is called [other product name]. And you can ….I am thinking of buying one on EBAY for old time sake.

Then people thought there is still something you can do with these sensors so they …at the time….there was something called set top boxes and people wanted to build a cursor controller for that and they decided to put a lens in front of this thing and basically use that motion detected by the mouse…so the way the mouse sensors works is just a camera and it takes pictures…very low resolution pictures, like 32x32…and then it rasters like 1000s of times a second and then it compares one image to the next and

correlates and then calculates the motion between one frame and the next and so it measures x-y motion of the image, which if you have a lens, becomes angular motion.

Q: Were you involved in making the mouse sensor?

I was applying it. Because a lot of people had ideas and doing stuff with the mouse sensor and so the interesting part of the story is they took this to [company] and said he hey….they were building set top boxes at the time…this is kind of a long winding story…it is just….[company] said….why don't you make a mouse out of it…"Why the mouse already exists, it's got a rubber ball in it and it costs 25 cents." And they said "Because 30% of our support calls are for clogged up lint in the mice and that costs us a ton of money." And so that's how that thing got invented in the first place. Part of this story is how one thing leads to another. You don't even know what people want unless you talk to them. That's kind of the message I see.

That became the mouse and I started to look for other things to do with the camera image motion sensor.

Q: When you say it "became the mouse". You are handed this sensor, then what do you do with it after that to become a mouse?

So that…[company] did that part…we built a prototype of that…which is just a…this thing you could move along and make the cursor move, but [company] actually turned it into a mouse.

Q: How did you go about deciding how to make the prototype?

We have a lot of engineering skills in the group….it was pretty….once you understand how the mouse communicates with the PC, then you just build…you have to adapt a circuit to work with that protocol. I actually have a video of the image stabilizer.

Q: [clarification] So you were actually building a circuit and then coding some stuff on top of it.

Right.

To give you an example of it, I…I have it in Dropbox if I can get enough bandwidth here…it might just take a second to find…I am sorry I am keeping you…here it is… hope it plays windows media files…so here is the little video we made … [shows video]

That's an intern I hired to do that…he built the software for me…

Q: Can you walk us through…you decided you wanted to build this thing…can you walk us through in depth how you went about making it…

I am an electrical engineer and the circuit part is simple enough…actually in that case…what did I do? …I think I built a PCB board and a USB interface on it using a commercial microcontroller and something called an FTDI chip, which is something that converts serial output on a microcontroller to USB. And I knew how to generate the X-Y signals from that but then I hired this intern to design the software to communicate with that…so he had to take the cursor signal…that TV thought it was a mouse…I mean the computer thinks it is a mouse and it gets x-y motion and we had to convert that to x-y motion and all that software was written by the intern…so the signals coming out of the mouse chip are x-y

coordinates…are motion coordinates….and then we convert that…those are just numbers and we convert that to motion…and he showed you those graphs on the screen …and from that motion we can calculate the angular deviation of the image…based on the focal length of the camera and the lens on the…so it is pretty straight forward to do that once you have the motion sensor…

So the point is that we build prototypes of things to show people and get them interested…because showing people power point is all…first you learn a lot by doing things…discover things you didn't think of …and then it is much more credible when you go show somebody … I think it is ….we continue to do that with [company] …try to make things and show them to people. Come up with an idea, usually it is stimulated by talking to somebody else. Sitting in a cubicle and thinking of the next thing is not going to work. So I firmly believe in communicating and trying to get out and talk to people….discover opportunities we can…in that case it was leveraging existing products…at [company] it would be glass.

I can tell you about some of the things we did there…

Q: PCB board…did you design? Multiple iterations?

In this case just one [iteration]. Because it was a pretty straight forward prototype.

Q: [Clarification] So just built one prototype and then…

And then showed it to the business groups and they got interested, seriously, and started doing the markets research and all that…the fellow's name is [Name], who I am still friends with…he then…right about then [Company] split off from the rest of [Company]…[Company] became [other company] and the whole chip …that mouse business went down. And what [Name] says is that they looked at it for awhile…did some studies…and then it didn't pan out. That's what happens to most things actually...most new ideas…you have to get lucky…it is like a ….it is as rare as an eclipse…all the business units have to line up …the time is right…and fits with the company….you have to find people willing to gamble on stuff…every company is a little different about that process.

Q: How did you decide your prototype was good enough to show to the business group?

If it looks….that demo I showed you…it looked like it proved the idea, then that is good enough.

Q: Want to talk about more recent project?

So let me give you some choices….in one case…I call it phosphor and glass project. I went to a company, also spun out from [company used to work for] …asked them what [current company] could do for them, and they said put phosphorous in glass. We don't do that in our lab, but people [at headquarters] can…so we started a project to work on that…that's one project

Another one…a case where no one really asked for it…we built a…when I first joined [company]…my boss told me to do something in displays and I said, "I'm not gonna do a display" but there was a lot of interest in touch screens, so…big touchscreens, so we developed an optical touchscreen…I have videos of that…but the trouble that is it is not a business that [company] does. They like to sell bulk tank glass and this is more of a system and that takes a different kind of…you have to have a different sort of customized products and hand-hold people…and I think it just didn't fit the company. But it worked great.

One of my colleagues gave [university] some money to do something with glass and they made glass speakers…and so…they said it sounded better than window glass…and oh that got [company] interested…so we built a bunch of prototypes of that, showed it to [other company]…built some…and it didn't sound quite good enough and it cost more money…so most of these things are failures

Q: Tell us about phosphor and glass project

So not long after I joined [company], I went to talk to people…people I know. [Company] spun out of [Company] also…and LED company bought by [bigger company] and they are out in San Jose…and so I arranged to go visit some colleagues there and made a presentation of [company I work for] and asked them "What can [company I work for] do for you?" And they said, "You can put phosphorus in glass." Most white LEDs as blue LEDs and they put these color-converting phosphors in front of them….absorbs some of the blue light but a little leaks through and then they emit yellow, red, and green, and then if you get the mixture right…which is really hard…then you will get white light out….[Company] makes high power LEDs for things like headlights…so they need the material that holds for phosphor at very high temperatures…good thermal conductivity…these phosphors are powders…a popular one is cerium doped YAG….you have heard of YAG laser before…but it is a crystalline material….about 10 micron size particles in a powder and mix them with silicone…and then they glop it on top of an LED…that's the cheap way… Getting the right thickness and color of one is actually pretty hard…but silicon's got really high…first, they have really poor thermal conductivity, so the little phosphor particles get hot because they are suspended in goop…and secondly, the silicons turn yellow after you give it really high power for a long time…so they thought glass is more durable…so I say oh great and I go to [headquarters] and there are a lot of scientists and people there and pitch the idea…what I find is that they get excited when they find a real customer for something because a lot of them are really doing fundamental research on glass materials…they are kind of isolated it seems …so they got interested and we tried a bunch of things and it took a couple years…it takes a while when you are doing materials…built prototypes for them…and then…it works really…that hit a snag that seems to be maybe making a comeback…the issue was that [company I work for] would like to sell this phosphor in glass…which is made by mixed powdered phosphor with powdered glass…then they mix that all in a paint like material and then they do something called tapecasting…where they just…it is the consistency of latex paint and then they pour it on this plastic sheet that is the tape and then they have this wiper blade that comes across that is set at a fixed height, so then you end up now with this skin that is a controlled thickness and they dry that out and then heat it up and burn of the binder they call it and melt it into a sheet. So this color control I mentioned is a big deal because each batch of LEDs is a slightly different color and you need to adjust it and so having [company I work for] in that manufacturing loop was difficult, so they said NO. But then they decided…I got a call back saying, "We are still interested, so can you just sell us the glass?" The powdered glass, so they are doing that now. They have their own group in [city] Germany that's a phosphor group and have tape casting machines, so that's what I think is going to happen in the end, not as big as business for [company I work for] as I would have liked, but it is something they are actually selling. Again, it is connecting people.

Q: What was your specific part in this?

My role was in this case…the interface between [company] and [company I work for]…they were nearby, we sort of set the specifications…I go to [headquarters], work with them to …they do all the science…they did all the science…so I was more or less a kind of ….I knew what the requirements were …[company] supplied the phosphor materials…we mixed them up…My role is more of a marketing guy …or something…I'm not sure what the name is exactly.

Q: What does mix them up mean?

So they take the powdered glass, which they call frit, and they have a laboratory there…and it is like a kitchen…literally they have mixers …some of them were more paint mixers…you've seen the paint shakers…they add the binder, it is like palm oil and it is not quite viscous…if it's a little too viscous, lets add a little bit of….I don't know…these different …over the years they have developed experience in how to develop the right thing…viscosity for these tape cast materials and then there was a tapecasting lab where they have this machine where they would pour the liquid in, swipe it across, and make the samples which were then dried under a heat lamp and then put into a furnace on a high temp plate…this stuff melts at 450 C, it is a low temp glass because they didn't want to destroy the phosphor materials…and they have different phosphor…some of them are red, that are more sensitive to the high temperature…so it took a lot of experiments with the glass composition to get a low enough temp glass that didn't degrade the quantum efficiency.

Q: Constraint of low enough temp. At what point where constraints defined?

The people at [company] gave us some guidelines, but it all depends on other factors…on oxygen…we learned we had to put it in a nitrogen furnace instead of a oxygen one to keep it from oxidizing the phosphor…literally the way…there is a guy named [Name] who is a fellow that has been around a long time…I first came to him and asked him what glass we could use …and wheels turning…we go into his office and he had like a lab that was three times the size of this and it was just surrounded by filing cabinets, so …he says "How about his one!?" and in these file cabinets he had pieces of glass. And he says…he gave two or three samples and they have a shop where they grind it into power to make these frits, and then we got some samples from [Company]…I may have pictures of this stuff…

Q: How was he picking those 2 or 3 samples?

Because the temperature…has to be low temperature glass, it has to be transparent…lot of the low temperature glasses are opaque, which wouldn't do at all…there were only two or three choices…of course, the glass composition is more than one material…we file patents on this…there is a bismuth based glass and an antimony one, so those…you can look them up in patent literature…so there is a lot of know-how there…how to make the frits, how to make tapecasting and you take advantage of those skills that exist in that institute already—that research group.

Q: Were you testing the color in the end?

Yea, we had our own lab and there may have been remnants there…it was in [Name]'s lab…on the other side of the table from yours was a spectrometer and integrating sphere, so we did our own measurements to measure color and quantum efficiency, but of course Phillips had their own method too, so we just ended up comparing. And then they built them into LEDs.

Q: How would you determine whether you liked the color? Or it was a good enough quantum efficiency?

So the quantum efficiency…we wanted better than 95%...we had a spec, and then the color…we had to hit a certain coordinate in the color space…there is a well-defined, numerical value for color, and there is a little window it has to hit.

Q: How did you decide what window you had to hit?

So it is basically the thickness or concentration of the phosphor. If you are too blue, then you have to add more phosphor.

Q: [Clarification] So you were sending that info back to [headquarters] and saying I need with more phosphor …

Or less phosphor…yea

Q: Or do you ever use different types of phosphor?

They had…we started with the common one…which is the Cerium-YAG one…easiest to work with…when we had that mastered, we went to …wonder whether I have any pictures in here…it is so old that I have deleted some of them…

Q: So starting with that easiest one…

That went pretty quickly. They want more…this phosphor gives something called a "Cool White", which people don't like. It is 4400K color temp. I don't know if that means anything to you. People like the warm light, so we had to add phosphor to it, and I don't have pictures convenient, and so we had to work…the red phosphor was a lot harder, since it tended to degrade at high temps, so we had to adjust the glass composition to bring the glass temp down and that was done by…I just tell the guys in NY we need to lower the temperature…so they did that…so there was this interaction, it went on for a couple of years…

Q: And you went through like hundreds of different mixtures...?

I would say probably a hundred.

Q: Throughout the process of developing…what are critical decisions you made?

So…I think the critical decisions were…I think the most difficult part was getting the red phosphor to work …and so going to talk to scientists in [headquarters] and figuring out how we can go about doing that…and the decisions were to switch glasses or how to change the composition to get the temp lower.

Q: You went to a lot of people to get knowledge/collect info, but did you gain any new skills yourself?

You know you learn stuff by doing. I never really …there are so many [specialty] scientists there, I didn't really think there was any point in me developing the glass part, but learning how to color measurements, quantum efficiency measurements…how to control the effects of temperature….you learn skills doing that kind of work…

Q: And how did you learn those skills? Did you…

Well a lot of stuff you can just find. Actually if you want to do quantum efficiency or actually color measurements there's software you can buy from ocean optics…you just call them and find out…just buy the software and that's it. You know. It's poking around the internet and asking people to find out what you need to do.

I have to say this…I have learned…I have worked in so many different things since I left school…I learned tons about stuff I never …more than I ever learned in school.

Q: How did you store all this info you gathered and keep it straight?

We have a system…actually a database for storing the data. Actually it is getting more and more standardized because …actually you can imagine [company] is [X] years old…they have been doing glass for research for 100 years or something. All of this stuff is in notebooks or this room with this guy …just knows where all this stuff is…and that is a problem. And so there is a big effort to organize it into …actually they want to use artificial intelligence ….learning algorithms to exploit all this information and simplify the …they've got 50,000 experiments in there…so to have it sort through…you just tell it what you want and the software will generate it. So there is a big effort going on, maybe 50 people working on it.

Q: How did you know when you were done? Good enough?

We got toward the end and we started talking with [company] about the business model…and we had the target quantum efficiency and thickness of the material and size…and we diced it up successfully into the little chips they were going to mount on the LED. It would be mounted directly on the LED chip. And then this whole business about the…who is going to do what…are we going to be part of their manufacturing system…they are going to get a new batch of chips, they are going to need a slightly different phosphor composition, how are we going to manage that…that is where the difficulties came. It was probably something we should have addressed earlier in the whole plan. And it seems to have gotten sorted out by, "You just sell us the glass powder and we will handle all that stuff." So that's really what…I thought it was canned for a year or so, but now it has come back.

Q: [clarification] so you sell them the glass powder and the phosphor?

No they have their own phosphor. They are proprietary [unintelligible].

And we are still modifying it. I just talked to one of the engineers…I was there in April, and he said, "Oh we are changing it again…" and so that is still going on. I don't know whether…when it is going to end, but it is just still going on

Q: You had also mentioned thermal features at the beginning…

So glass, it turns out, has 10 times the thermal conductivity as …you don't think of glass as very conductive, but it is 10 times better than silicon. And the way you get the heat out is to mount the chip right on the LED, which is the heat sink for the…so the heat it is generated in the phosphor and goes down into the chip substrate and out, since there is no other way to get the heat out of the thing.

Q: [clarification] So using the glass over the silicon was an improvement…it wasn't a…

Right significant improvement.

No. Glass is just…silicon is just the worst possible thermal conductivity of any substance I know. 0.1W/m Kelvin or so.

Q: They were just using that [silicon] before in industry because it was easy?

Right…it is pretty good in taking the flux from the UV but it is not…but if it is a low power LED it last a long time, but if you want to generate a lot of power….[company] main business is auto headlights…and there you need a very bright source, collimated beam. It is kind of a specialty market, but the benefit is the Chinese are selling all the cheap home LEDs and you can't compete with them so you have to sell these high-end, high-performance LEDs to make money.

Q: Other solutions considered?

Well, I had other ideas of how to get the heat out of things, but I didn't share that with [company]. In fact, I think we might…in fact we are still doing some work…I think I showed you the backlight work for displays…so we are still working with these quantum dot phosphors instead and keeping…heat management turns out to be critical for those applications too, so one thing leads to another, so I learned a bit about the inorganic phosphors and now we are working with these organic phosphors. Again someone I know who used to work with [company] and left and now runs a company called [company], which makes quantum dots and so …he is supplying some for us to work with.

Q: You had others ideas you didn't share. How did you decide what to share and not?

So if it didn't really directly affect their application…this particular problem …you just think of other things…and I didn't see the point of it ….it wouldn't have made a difference…

Q: So you chose the simplest one or…

So the simplest one, which is what they were doing…just sticking the chip down on the LED. The idea I have is related to heat pipes. Do you know what heat pipes are? Again…you learn things…they are way…they are used in laptop computers…and they transfer heat by vaporization of a working fluid, which condenses in another place, so you have a pipe literally, and a cold end and a hot end, and the fluid vaporizes, transports the vapor down to the…then condenses and is transported back on a wick…all of this is hidden from view…but I saw this first when I …I have another friend who works for a company called [company]. They spun out of [university], I think. They do industrial design and they bring visitors in and they have this heat pipe, this copper tube and they stuck it in hot water mug, and you can feel the heat instantly at the other end. Wow it's like the best thermal conductor there is. So you can implement that concept in LEDs then…

Q: So why not do that then?

Well you could still that. But I am not in the LED business but I am not sure if we filed a patent on it…maybe we did. Again, it is like seeing one thing one place and…that to me is like applying…the creative part is knowing all these things and knowing how you can apply them to different/other problems.

Q: So you spend a lot of time going to other companies and talking to people? Conferences…and…

Yea conferences are good. I am working on a glucose sensor right now that comes out of a talk I saw…I haven't done human trials. [Company] is in the business of life sciences…they make cell growth flasks, which are plastic by the way, which are polystyrene…now they want to go into the monitoring business, because they incubate cells in these flasks and they have to feed them glucose and …. And so they have a really bad idea of how to do it, and I saw something better at a conference and so I am building a

prototype of that in our lab. It is something someone else did and so …the tricky bit I am learning…again you learn by doing…it is temperature sensitive and I don't have very good temp control in the lab.

Q: How many hours a week to you spend talking to people?

Not as much as I should.

[showing picture] Here's this thing…in an incubator…a circuit board and …it works, but I am not yet happy with it. It is too temperature sensitive and when I open the door of it to put a new sample in the thing it takes two hours for this incubator to settle down to the same temp. So I bought a little mini incubator and I am going to try doing it again. Hopefully it is a little faster. Again, I went to a conference I heard this other problem and I'm like, "Oh let's just…" and it is simple enough to build. It might work on humans…once I get this working I am going to put my finger on it and drink a coke…I never drink a coca cola, but I bet I can get a sugar spike out of that, that I can see on the…

I don't know if it will work.

So I think getting exposed to a lot of different things, even if you don't understand them completely and seeing what people need and putting these little bits together. That's the fun part for me.

Q: Critical components of being an expert. What does it mean to be an expert?

So I think practical work in the lab matters a lot. I think you can…first of all it is more motivating if you are building something…to really understand it….and secondly you learn all the things you didn't think of. It's kind of …learning by doing is really critical. I think lab courses are very valuable in that sense. And I think having….when I was an undergraduate not at [place]…the senior labs were like teams of people working together to build more complicated devices, and that was a lot of fun, interesting thing to do…I think that kind of…that's something like people would really do in the real world…actually like not just one little circuit, but like a bunch of things that had to interact with one another. And you had to design the interfaces, and it was fun.

Q: Difficulties in mentees?

Well I have been lucky enough to have nothing but nice people and interested in learning and so I help point them in the right direction. Like today I have a fairly new employ and he wants to do this project and I told him "Look people have been working on this for 20 years, you should go to the library and look. Here are a few examples…before you just go off and reinvent something that someone else has already done." That's just today as an example. I showed him a bunch of things…and so…I think that's useful.

I haven't really had to do hands-on work them. I do give them advice on what circuits might do this or that but I don't really…and suggestions about how they might implement something.

Q: Phosphor and glass project…someone else who is new working on it. What troubles might they run into?

So I can imagine someone coming there, particularly if not from [headquarters] and know about glass—"Oh that's interesting, let's write a report and send it in." And then nothing would happen. I think you

actually have to go and talk to people. Because no one reads reports. That would be the most likely thing.

Q: [clarification] So you think the project just wouldn't have taken off.

Probably. Possibly anyway.

Q: In the process of iterations, were there things that someone with less experience would have done differently?

So…one thing about this project…once the people in [headquarters]—these senior scientists got interested, it sort of took off on its own. I didn't really have to…I was then kinda of…I organized meetings, and we reviewed the progress, but it was more a leadership role. And I don't know that…a really inexperienced person would have been comfortable in that role. Not knowing how to …you have to learn how to deal with people. I know you said you thought in engineering you wouldn't have much interaction with people…that people sat in a cubicle, but it is really not that way. I think it's all about interactions. To be successful, I think.

Q: How do you decide which ideas to tackle?

Well first of all, they have to fit [Company]. And I learned a little about…you know you learn by doing…about this building complicated systems…even building like eyeglasses we were talking about is not something they would do, but some elements of it—selling the glass might be. But building…

Sort of losing my train of thought…

You were asking me…

First of all, I have to be excited about it, it has to fit to [company] somehow…I have to rationalize in my mind how [company] might make money out of it. Those are the two main things.

Q: If you have 5 ideas you think [company] can make money out of, how do you pick?

There are better ones always, you know, I think are reasonable…choice. Cuz I pointed out some of these things come from the outside…people asking for…so there is an obvious market if they are successful, but if it is something that comes from…like this glucose sensor—nobody is really asking for that, although, so I am not sure…that's riskier from an organization stand point.

I think if there is outside pull for something that is always important.

No one in [headquarters] would have done anything [on the phosphor project] if it weren't for big company asking for it. So that outside interest in it…

Q: So how come you decided to do the glucose one?

Because it is simple. It doesn't cost much. A PCB board and some plastic. It doesn't…and I can dabble with that in my spare time. And I have a review of that in one month, so I am trying to get some data out of it, and we will see where it goes from there. Then we will have to start a new project.

Yea, if it is really simple, then doing the experiments doesn't…I spent $100, but the glass thing is a lot bigger. [Describes the glass shop and how expensive it is to run.]

Q: Do you use models in your work? How do you use them?

So the glucose sensor, that's all using electromagnetic theory, you can design that and I did that. And that uses a particular tool that's available [online?] called HFSS…I am not sure what it stands for…high frequency simulation something…and I had used that from years ago…it's a steep learning curve if you are starting from scratch, but I had experience from my previous work using it, so it was pretty quick to do that.

Electrical engineering industry 1

I will tell you about the blade tracker project.

To do diagnostics on a rotary helicopter blade…eventually like to do when its flying…when they are firing it up and make sure the blade… You are setting up a timing gate to make sure its velocity and variations in it…also so you can adjust attack angle and stuff…for doing diagnostics on a helicopter blade…optically.

So it is an active system in the sense that you use a laser to reflect off the blade and that laser is split into two to form two sort of spots out there in space that the blade intercepts as the it goes by and you collect the return radiation onto a detector

Q: How much was you were told you have to do this vs. you decided what the best solution was?

All the ground rules were trying to set up a timing gate to measure the blade velocity.

And that was it.

Q: walk me through what you first did

Well obviously a laser would be …

Well it is basically a lidar type system you are doing here

The problem turns out that the resolution they want to measure the blade to is like 3mm and with the revolution of the blade and the blade is like 8 feet and revolution 10rpm that works out to a rep frequency of the signal of 200kHz and you then you need 20ns pulse so a rep of 200kHz and pulse of the signal coming back …of the edge coming back… edge position of 3mm means you have to do like a 20ns pulse…so if you want to tell where the edge of the blade was to within 3mm

This is very different than most lidar systems because here you are trying to look at only a small little section of space. You are only trying to look at something that is 3mm across and then you have to put out a lot of power because the blades are like at 45 degrees to the angle to the beam…and the blades are very black…matte black, so the reflected light is in the 2 percent range and that reflected light is scattered everywhere. This is a very diffuse…there is very little reflection. It is obviously dependent on the blade surface quality. Purposely made for more diffuse reflection. Let's say you are sitting back 8 m or so (5-8m away). The typical signal is in the nanowatt range. And so you are going to have …and the decision was also made that we were going to do this CW, not pulsed to make it as simple as possible, so all you are doing is sort of chopping the beam with the blade, and you are looking for the reflection from the blade, so the signal back would be just a rect function. The blade is there then not there, but then you have to worry about solar background. Solar background could be so strong that you don't even see the blade…it is swamped by the solar background. And to get rid of that you could go with a pulsed type of system where you are pulsing at 200 kHz as opposed to being in CW, which we decided to go to. But then there is a cost bogey—they decided to keep this thing under $2000. Well you then have to have a laser with 200kHz rep rate and 20ns pulses. Those 20ns pulses you would want to have a minimum of like 200W in these small little pulses or more. The issue there is that the only lasers that really do that are Ytterbium fiber lasers, which do that really easy, but cost too much, like 10-15k. Yea so you can make a system with that really slick and that you know…the simplest system you can do…all you have is a pigtailed laser…a source going into a 2x2 coupler, those two outputs feed to two lenses that collimate

the light out that head out to where the blade is, reflect the light off the blade, comes back to the same way it came in (the fiber coupler), 50% of the light obviously goes back toward the laser and the other goes to the detector, but everything is self-aligned. You are using a common outgoing and incoming leg, so there is no alignment, so the field of views are matched. You want the field of view of illumination to match the field of view of the collection of the detector. And so it is basically a plug and play system—there is no alignment. Plug everything in and it should work. That was the original idea I wanted to go with, but try to do CW. Just that the losses…the biggest lost is the light coupled back into the fiber …because it's a single mode fiber…its only going to be what is matched to that single mode so there is a huge loss there, so you get less than a percent of collected like back, so you are going to have to throw out a huge amount of power to be able to get a strong enough signal. That was the preferred approach, we didn't go with a pulsed approach just because ….it still might work...you'd have to go back and look at it in more detail. You do phase detection like a lock-in amplifier, modulate at 200kHz and try to see if you can pull the signal out of the solar background and stuff but the decision is currently made to do a parallel channel approach so you have a separate illumination leg and collection and we showed that would actually work. You can get away with a 100mW CW source and like a 2inch collection lens and be able to see a nice strong signal. All these wavelengths are at 1550 because you want it to be as eyesafe as possible so 1550 basically keeps the light from getting to the retina, it is only being absorbed at the cornea. You can have an average power of 100mW at 1550 but we could have peak powers of 6 Watts if it is modulated just to get the eye safety issue. But eye safety is not absolutely required for some applications, so we aren't worried about that right now.

Should have had my viewgraphs up here, so I could remember it.

Q: so if I understand correctly, the final design you decided on…

It is not a final design, it is a straw-man design. We did a straw-man design which we built up in the lab that was separate outgoing channel and separate collection channel so they are separated from each other and we just set it up so that we could see the signal off a Apache helicopter blade and you could take it outside and see the signal even with the solar background and you obviously use a bandpass filter, so you basically bandpass the 1550 laser line and have a band pass filter wide enough that you reject the solar background.

No modulation there, just CW. The laser is always on, the laser comes by, you see a rect function come back out of the detector when it is going across the blade and you see basically …we didn't do a timing gate, we just did one leg of the gate…just to show that we could see the signal.

But that approach is much more complex than the fiber approach. Now you have to line these two channels up and maintain alignment and if you ever mounted this thing on a helicopter with all the thermal…so it could be done when you are flying around, you would have to have a really robust system mechanically and thermalized so you didn't get misalignments, which with the fiber approach nothing is going to go wrong there alignment-wise except displacement of the fiber relative to the lens , the outgoing and also the incoming light can be moved/changed, but that is an easy thing to make robust.

Everything else is just fibers plugged together.

We did try a multimode approach instead of using single mode fiber to try and improve collection efficiency, go multimode…so instead of having like a 10 micron core size you could like 100 micron core size and you could collect a lot more energy from the return. The problem is there you have to make sure you excite all the modes in the fiber else you touch the fiber and you excite different modes and

you see different signal at the detector, so you would have to then have an element in there that excites all the modes of the fiber, basically a mode mixer, so that the output will always be the same, it is not going to vary. We didn't go that way either. There are all these different variations to try to solve the problem, but my goal is always to try to do it the simplest way—that is why the single mode fiber approach works the best but the problem is cost limits you not to be able to solve the problem. Most LIDAR people are looking at 10kHz type of pulses and not trying to get a 3mm resolution basically. Like the laser sources on cars…there…only cost like $30 but they are edge emitters, so trying to project that edge emitter out there at range…they'd have to use beam shaping optics to take the rectular? emission output- its 100 microns by 10 microns and we want a 3mm spot, so the complication there is adding beam-shaping optics.

Q: How you chose LIDAR? You said natural choice…but for someone who is not an expert in optics, how did you come to that conclusion?

Well if you want to be out near the edge of the rotary blade of a helicopter, so …right now what people do is a passive system and it is like they are looking for the shadow of the blade as it goes across the detector, but that is a pretty crude measurement, right? Because obviously it is not going to work at night and it works great if the sun is your source, but the shadow cast by the blade at 8 meters tends to be pretty fuzzy, so the resolution is going to be nowhere near a spatial resolution of 3mm. So they were looking for a different method to do this, now you could maybe …a radar approach ..or maybe terahertz…it is longer wavelengths basically , but the idea was here, if we could use 1550 light—that's the common communication length, so there is a lot of devices being made at 1550nm, so we could sort of ride on the coat-tails of the 1550 work that has been developed and keep the price down. So you could by a 50mW single mode laser for like $500 –pigtails and stuff—then the fiber coupler can be had for like $100. And the detector you can get for $300 with amplifiers and this is just buying onsies twosies. And all the glass …all the AR coatings and stuff …seemed like a good way to go with a cost sensitive program …use components that are already being built for other tasks. …and it is eyesafe too.

Q: What's the next steps?

Well since we determined that the all fiber approach wasn't going to be feasible due to the cost of the laser source the idea now is to go back to the original breadboard which is independent outgoing and return leg and try to fold those two together so you would have like …what was done in the lab original was two separate lenses side by side. The problem there in that approach is there is parallax. As the range changes, the position out of the detector of the return from the blade is going to walk across the detector, so it means the detector has to be a bit wider to be able to cover the range. Say you want to be able to measure from three to 8 meters distances to a rotary blade you are going to have walk-off that return across the…cuz' you can't realign stuff you just leave. That causes you to increase the size of the detector which means you are just going to collect more solar background. Cuz you want to have the field of view matched and one way to match them would be to fold one leg—the outgoing leg—onto the return leg with like a diagonal mirror, so you sort of bring the light, one channel up and fold it onto the axis of the collecting light so then out they come colinear, so then you get rid of parallax going on as the range changes. But then the problem with this is that you are just adding more mechanical components that would become misaligned in a harsh environment—vibrations—mounting on a front end of a helicopter. Initially it is not going to be done that way—it is going to be done just looking up at the blade when the helicopter is sitting on the ground to do diagnostics. So can you come up with a robust mechanical solution? The mechanical guys are looking at that to see…

The other way to do that would be to core out …let's say you have a two inch lens…core out the center of the lens and put your outgoing leg in the center of the collecting/return lens. So you core it out, stick a lens in there like 10mm lens…have a fiber feeding that lens, so the fiber would sort of walk in to the center of that lens…so it would be an annular region in the center...the lens takes the light and images out to the rotary blade and then the collection comes back along the same back, but goes to the outside by this oversized lens—the outer part of the annulus. Then a detector behind it, it is like a secondary telescope. The idea there is that it would be much more robust—you have a fiber mounted to the lens and that lens is mounted in the cored out part of the collecting lens so you sort of got a monolithic piece, so you can envision that being fairly robust and stuff. But that is not what we are going to do initially because that requires some lenses to get cored out and the idea was to try to make this as simple as possible with all off-the-shelf [unintelligible] elements.

Q: So what is the next prototype that is going to be built?

Well it is going to be using the elliptical diagonal lenses like you see in secondaries and mirrors for folding the light into the center of the collection optic. So it sits out in front—those diagonal mirrors sit out in front, so that all can be done off-the-shelf [analogs?]. The big thing is if you can come up with a mechanical assembly, hold everything in place very robustly.

Q: [Reiterate what he says for clarification]

I basically give the mechanical guys the optical layout. They then come up with the mechanical design in CAD…solidworks…ProE and come up with a mechanical structure to hold these elements, also give us minimum amount of alignment, 'cuz the more alignment you have, the worse off you are going to be in terms of…that will potentially cause misalignment so really you only want to have to align on thing and that one thing would potentially be the detector. So it is like the outgoing laser would determine where the detector needs to be positioned, so you put that center thing in and wouldn't do any alignment there the only alignment would be to focus the light onto the detector, move the detector and focus it in the x-y so the return light hits the center of the detector and then lock that detector down. So there is only one element that needs to be in 2….3 degrees…x, y, and z. Assuming that the mirrors are held really good and stuff so there is no possible way they can change their orientation/position and stuff.

Q: How many iterations will this go through before it reaches "we are done" stage and how will guys know when you are done?

Done would be something that is ready to go into the field. Done would be if it is ready to be mounted on a helicopter. That is what done would be but there's gonna be one iteration here where you basically make this sort of diagonal fold-in thing to show that it does work…outside and stuff…looking at helicopter, but the next iteration then would be…well is this the best way to implement it or do you now go and spend more money and core out lenses and assemble it in what would be a potentially much more ruggedized and thermalized design. If you are that far…that iteration, then you are fairly close to being done and you could then…it would be nice to maybe look at modulating the laser source …and a lock-in type of detection…to try to gain some improved signal-to-noise but that would be sort of a side bar. You implement that and would potentially allow you to reduce the power of the laser and save some money there but not have to spend a lot more money on electrical components to do the lock-in.

Q: What kind of info did you have to collect?

Well you had to start off with…since we are working…had to worry about solar background. You had to first determine the bandpass you were going to work over and calculate how much solar radiation is in that bandpass that you are going to work under, so you had to go get those tables and do numerical integration to turn …determine how many nanowatts of power at 1550 …oh yea, well originally, the idea you could have done this in the solar blind, there is obviously regions of the spectrum from the sun that when they make it to the earth—sea level—they are totally absorbed out. So there are these solar blinds, obviously stuff –stuff deep in the UV that is solar blind and then there's sort of absorption bands around 1300 and stuff that are …. If you could come up with a laser of the right wavelength, it would be like you are working out at night all the time, but that approach was thrown away because those…it costs big money to get a custom laser to do that. The first thing was to determine what the solar background was and then set up a model that projected light out onto the blade and then collect the return from that and show how much light was falling on the detector…how much radiation falling on the detector. Then you could have the solar model in there too so you basically have a plot of the solar background relative to the actual blade return signal. That would basically then determine how big of a collection aperture you need. Smaller the better in terms of collection aperture because they don't want to have this gigantic thing that looks like a dragonflies' eyes out in the front. It would be nice if you could get away with like a 30mm aperture but you might have to do 50mm aperture.

Q: What does model mean?

I was using CODE V basically. So that way you start with a source, collection optics, and then image out or collimate the light out—you can do it two different ways—collimated would be the best in the sense that that way you don't have to do any focusing at all—just make sure that the collimated be is such that it is 3mm in diameter or so and stays that diameter from like 3mm-8mm [think he meant 3-8m]. And then when you do the actual modeling it is really the return leg you actually do the model to determine how many photons you are going to get back onto the detector, so you assume an angled source that is Lambertian for the blade and it is a certain size and that is the spot size that you projected out around the blade and then calculate what the collecting energy is on the detector through your collection optics.

Q: Were these all skills you already had? Or did you have to gain new skills?

Nah…I have looked at solar stuff in the past and so if you know where to go to get the tables …radians or steradians …then it is an issue of is it a sunny day, cloudy day, all those type of issues and obviously it is never going to work if you are looking directly at the sun. So you have to stay within …what's that called--the area around the sun ….you know you gotta stay within 10 degrees away from the sun. And all the other modelling and aspects and all that stuff has been done before in other programs basically…just using CODE V and stuff.

Clarification: [Referring to] Modeling of the return signal strength and the solar.

But the mechanical stuff I don't worry about that and the electronic stuff I don't worry about. That is someone else… you know …you got a team and you want to make sure each member of the team is doing what he's expertise in and then just fuse them together. I've worked with the mechanical guy a long time so we know how to work…

Q: How do you interpret your results from the prototypes?

I made a model calculation of what the signal strength should be on the detector…first we had to go through and calibrate the detector out, which is done by putting a source of a known power a certain distance from the detector and then calculate what the amount of optical power was falling on the detector and what the voltage out would be so you could get the watts per volts or mw per volts ratio. Knowing that in our setup you can then make a prediction of what the detector signal should be and make the measurement in lab and show that the model and the experimental results agree. And you can do the same thing with the solar. Take it outside and see when you project your [unintelligible] how much the solar is going through the bandpass you have…it is like a 50nm bandpass…I can't remember it exactly and so…the amount of signal recorded was comparable to what the model showed.

Q: How did you show the 3mm resolution?

That…didn't worry about that right now…well…for the focused spot out there or the spot that we collimated had to be close to 3mm…you know we were saying we could live with 5…so the spatial size of the spot of light falling on the blade.

Q: Difficulties in problem solving you see in mentees

Well one thing is they want to do everything basically. [Laugh] You know…a lot of them would do the electrical, the optical, and the mechanical …as opposed to [Laugh] working in a team basically and trying to …you know…working in a team and using the expertise of the different people in the team to solve the problem. But that might be true of everybody fresh out of graduate school—they want to learn everything basically and stuff.

Q: Are there aspects they didn't think about that were important?

That is always the case. I was the same way. For example, people trying to figure out how big a lens should be. If it is a gaussian beam they gotta realize that a gaussian has tails on it. So they didn't appreciate …well gee if we clip it at 1/e^2 intensity point …sure you are going to get like 80% of the energy or whatever …problem is, it is going to cause diffraction effects. See stuff like that they are not appreciative of. If they haven't been trained highly in optics and stuff.

Q: What do you mean by trained highly in optics?

In other words, they had like one class in optics lensmakers formula and know what a gaussian beam is, but the idea is that diffraction effects can hurt you. If you cut at 1/e^2 you are going to have ringing on the focused spot, which can cause havoc. So there are subtle little things like that and a lot of times you have to clip it 1/e^4 or 1/e^8 if you want to make sure that you have a pure gaussian beam at focus.

Q: Do you think that this is something they should be learning in classes? Or is this something they should learn on the job?

Obviously if you take enough optics courses you will run across this. But the other way to run across this is working on a job and sort of …along with other people…that is what happened to this one guy…he didn't realize he had to worry about that …he was designing a system for 1/e^2 everywhere and he didn't appreciate that…yea…but then once he has been told, he will obviously remember that from now on.

Now…I don't remember where I picked it up…graduate school? I don't remember

But when you are modeling something, actually modeling, that would show up in the model. Obviously you would model your gaussian beam going through that aperture and see that this clipping is generating feet on the focused light.

And optics seems to be something that even in this day and age is not appreciated totally. People just think you can buy some store-bought lenses and throw stuff together and it will work. In a lot of cases that is the case, but there are other cases there is more to it than that, cuz stuff is not ideal. All these lenses have aberrations that add up.

Q: Modeling in CODE V. You are always using ray tracing? That is your scientific concept you are using?

Yup. Everything in CODE V is ray-based but they've got that wavelet model, which they put in in the last decade, which I use a lot. Basically models reality quite well. It is like Huygen's principle but instead of spherical waves they use gaussian beams. Problem with a spherical wave is that it goes all over the place—energy is spread out over 2 pi steradians. When you are putting light through a lens, the light only exists in a small little area, so if you use a gaussian beam as a propagating wavelet you can limit the spatial extent of it and it will go through the lens. It is a very powerful tool they got now and that is what I use for…well…my work. It basically takes into account diffraction…you don't have to use FFT to do diffraction calculations…it is all just this Gaussian beam wavelets…summing them up at the end.

Q: Before with ray tracing, did you have to worry about limitations?

FFT always generates artifacts and stuff. FFT approach only allows diffraction at a given plane in space where the wavelet ….hey…something clips…those wavelets are clipped and it has ramifications when you sum them up at the end.

Q: [Repeat back and ask for clarification]

Of course…you have to know the answer before you do it ….with modeling. You are just using the modeling to sort of reassure yourself to what you think the answer is going to be…what you feel it should look like. Or if you are doing something for the first time you have to have it experimentally verified. Have to have some [unintelligible] from the modeling system. Gaussian wavelet stuff it is just amazing the …focused light…Fresnel zone type of stuff….all the interference patterns you see…it is amazing the wavelet will show that stuff. Looked just like the image you take on the camera with all the fine details in the interference structure and it is all there basically.

Q: Final comments on things that are important for kids to be learning in school.

Not really. [Laugh]. I think its….go to a school where the professors have all had industrial experience. In other words, so that they have sort of real world problems that they have had to deal with in industry.

Q: "Real world" vs. academic clarification

Like Arizona, when Arizona optical science center started all the professors came out of either ITech or Perkin-Elmer and stuff, so they had been in industry sort of learning on the job, sort of and stuff.

Q: How did that make them a better professor?

Better sorta idea of how industry actually works and what it needed. It is like …they taught me to try and do things as simple as possible. Don't throw the kitchen sink at the problem. Try to solve it with the fewest number of moving parts as you need and stuff. So you spend more time sitting there and thinking about it…refining it….but then you have to be careful…it can't be too simple and then you get side-swiped by something.

Q: Anything besides thinking simple that profs taught you? Still trying to figure out what you meant by bringing in real-world stuff.

Their experiences they had seen in their time of working. Sharing that with us.

Q: [asked for clarification]

Little sort of side bars. Cuz when this guy tried to move the telescope and forgot it was mounted down and the whole thing came tumbling down and stuff like that but…. The example there was double check twice before you do anything.

Medical faculty 1 (pediatrics)

CK: Ok thank you so much for coming in. So basically for this interview we are basically trying to get a better sense for how experts go through the clinical decision-making process. And so we basically wanted to ask you to recall a patient encounter sometime in the past where you felt like it really represented your clinical decision-making process, perhaps it was a challenging patient encounter, one that just stood out to you in some way. So feel free to take a moment to think about a specific patient encounter.

E: So kind of a framework that I would use for clinical reasoning and diagnosis?

CK: So we were thinking of an exact or specific patient encounter, so it might include a framework that you tend to use, but one specific patient encounter that you felt was particularly illustrative of that framework if that makes sense. And we'll be using that specific patient case to essentially walk through your thought process as a representative example if that makes sense.

E: Give me a moment... [pause] Well this was a patient that I took care of many years ago and so - should I walk you through the case?

CK: That would be perfect.

E: At the time I think he was around 5 years old. He had a history of asthma, and it was a pretty well-established diagnosis. He had some atopy and then was coming back recurrently for worsening in difficulty breathing. And so I think one of the things that I learned from this particular case is just being very careful about anchoring on kind of knowing what the past history is making assumptions, and then to kind of stop and rethink when something doesn't quite add up if that makes sense. And so the patient had the pretty standard treatment for childhood asthma, he started on his albuterol inhaler, would get steroids for steroid burst of about 5 days, and would improve pretty quickly, and would seem pretty typical. And then once he stopped the steroids, his respiratory symptoms would come back with even more severity. And so you know by the time he came to us this was a more progressive issue. Chest x-rays weren't done because you know per standard of care we generally don't get chest x-rays for kids with established diagnoses. But in this case because he's had so many recurrences that were more atypical and wasn't responding as we would typically expect, the outside emergency department got an X-ray. And they found an anterior mediastinal mass, and so at that point he was ultimately diagnosed with lymphoma. And the steroids is also treatment for the lymphoma and so that's where things got kind of muddy, so he would improve because he would get partial treatment for lymphoma, but then would have recurrence of symptoms once steroids fell off. And so I think it was a learning opportunity to kind of make sure that we don't anchor on a diagnosis and kind of stop to reevaluate, go back to the drawing board to think about what else like it might be.

CK: Thanks for sharing that story with us. We were wondering if you could maybe go back to the very beginning of that encounter, and what was like the first thing that you did with that patient that kind of set off this whole clinical reasoning process?

E: So I'm trying to think back. I don't know if a different case might be more helpful because I kind of came into the picture kind of knowing his X-ray results, so I'm happy to talk about a different patient where it was still kind of undifferentiated. I don't know if that would be helpful where - so I could tell you about another patient. I'm sorry about that [laughs].

CK: Not at all. We realize that you obviously see many patients every day, so if that means talking about a few during the course of the interview, no problem at all.

E: Okay so there was another patient that I took care of, he was a teenager previously healthy who developed vomiting, abdominal pain and some diarrhea and was seen at an outside ER and was diagnosed with gastroenteritis, needed fluid rehydration. And so I was at our community site and accepted him, and it seemed very reasonable. I think things that changed over time is that his symptoms weren't improving and so the vomiting eventually resolved but the abdominal pain was getting worse. And he was having diarrhea, and this is a pretty stoic teenager where he really wouldn't any pain. And I think the important thing was kind of recognizing that his symptoms were sort of out of proportion to what I would expect for gastroenteritis. I would expect gastro to improve day by day, and his just didn't seem quite right. So I think up until that point, I think he may have had an ultrasound to evaluate for appendicitis. And maybe they weren't able to see it, but ultimately we got a CT scan and it demonstrated the beginning of an appendicitis. So he transferred back to the main hospital, and then went to the surgical service for an appendectomy. And so I think the challenge for that case was kind of saying, is this kind of a prolonged - an unusual course for a very common thing, or is this something completely different? Is it a classic presentation for something else? And what is the risk of doing an additional test, which would be radiation? And what is my index of suspicion? So because he looked actually pretty well, but knowing that he was pretty stoic and it wasn't a very consistent abdominal exam.

CK: What do you think help you with making that decision? So it sounds like there were multiple things going through your mind, and what made you decide to actually go through with the scan?

E: Yeah I think the thing that stuck out was if I kept thinking about it, and if I'm worrying about it, then if I had that much of an index of suspicion then I should just go through and do the CT scan. Cause I feel like we do CT scans for kids back then a lot more freely, and people get scanned for a lot less.

AP: Can you go through in a little bit more detail what it was about this case that made you think it wasn't typical?

E: I think it was more the fact that - you know with gastro, I'd expect day by day - sure his vomiting had improved, but his abdominal pain wasn't getting better and usually that would improve day by day. And so at that point I felt like kind of I have to stop, rethink, look what is my differential diagnosis for this patient, what am I missing, what have I not considered, and then do I need to go down a different pathway. And so I think kind of the approach is kind of what we hope to teach in [course], so using the diagnostic framework. So thinking about the different organ systems, like what are potential diagnoses, you know just generically not thinking specifically about this particular patient, you know what are common things, what are can't misses, and then what is the typical illness script for these disorders. And then kind of going back asking the family more questions to say okay did I miss something, and then see which illness script kind of fits and then that would help me narrow down the differential diagnosis for that specific patient.

AP: So did you consider - you mentioned gastroenteritis and appendicitis, did you consider any other potential diagnoses in there?

E: I think - so it wouldn't give you diarrhea, but if he had some sort of testicular torsion, if he had something else like a malrotation and volvulus and causing vomiting and abdominal pain. It wasn't really classic I think with the diarrheal symptoms, but kind of going back and almost as if he was

undifferentiated to me and I didn't have the working diagnosis of gastroenteritis just needing hydration, kind of just starting from scratch and saying, okay you know this doesn't seem like it's typical and you know I need to go back and do it more purposefully because otherwise I feel like it's so easy to get biased by what the primary care doctor referred him to the ED with, and what the ED saw in him they tell you. And then you just get so anchored, and then you know you don't quite see things as clearly as you might if you were the first provider seeing them.

CK: And you mentioned that you ended up going back to the patient's family to gather more information. What kind of specific information were you looking for?

E: It was a couple years ago, I was thinking like either exposures, so anyone else at home who's sick, did he eat any kind of unusual foods like any raw foods, any undercooked. Because a lot of times it's not that families don't want to tell us, but they don't think of it. So but I think the more that you ask probing questions kind of just broadly and then being really specific, then a lot of times I find it jogs people's memories. So kids with prolonged fever you ask, you know your child played with any animals, gone to any zoos or farms or what not. And people are like, no no no. But then the tenth person who comes by and asks that question, then they're like, oh wait yeah you know they went to go visit their friend who has a lizard. And then you're like ah, there you go! [laughs] But again it's not like people are withholding information, if it's not a significant event a lot of times it doesn't stick out

CK: And did you end up doing other tests? I know you mentioned the scan, but were there other tests that you had to order in order to gather more information?

E: I'll have to think back... I mean usually I probably would have gotten a blood count, check inflammatory markers. But I think with his clinical symptoms and the scan, I think it would have been enough to make the diagnosis. We might have been checking his electrolytes if he was having a lot of diarrhea and on IV fluids and not eating very much.

AP: You mentioned that there was some decision-making, some like - you didn't necessarily want to jump into getting that scan, but what - was that the first thing, the first test you decided to do. Or like what was the kind of tests?

E: I think if I had gotten the blood test, that would have been easier and faster. But more definitively would have been some form of imaging.

CK: Was there a reason you didn't - you were taking time to think about whether to do the scan or not, versus you know just immediately feeling like oh maybe this is appendicitis and just immediately kind of getting the scan?

E: I think the fact that his abdominal pain wasn't as significant as I would have expected. And usually - and again he was pretty stoic. Usually kids are in pretty significant pain, the pain is pretty constant, it doesn't tend to migrate, and I think there was some atypical features I can't remember if it was right upper quadrant as well, or if there was something that wasn't the classic started periumbilical went to the right lower quadrant. And he had anorexia, nausea, and sometimes kids don't have any bowel movements. So I think it was a little atypical enough, but I remember thinking about it in the morning and then by I think around lunch time we ended up getting the scan because I felt like if I'm worried about it this much, then I just need to just do it. It will just be a lot more definitive, and it'll put me and I think the family more at ease.

CK: And you've mentioned a couple times that this particular patient was stoic. Can you speak a little bit more about how your perception of the patient, or your relationship with the patient or the patient's family, ended up influencing your clinical decision-making process?

E: My recollection's that the patient and family were very open, very reasonable, and very easy to partner with. My sense with that he would tolerate- his pain tolerance with a lot higher and even when I would press I would have to look at his face to really get a sense of like- I'm like does this hurt and he's like no - based on your face it looks kind of like it's not that bad it was a lot more underwhelming but there was just enough where it was odd enough and I didn't want to miss that diagnosis.

CK: And did you feel like during the course of your your breathing process that you ended up using any sort of basic biology information to help guide your your diagnosis

E: Basic biology, you mean like illness script for appendicitis or pathophysiology?

CK: yeah so we're thinking more a little pathophysiology but if it fits into the illness script as well that's fine

E: yeah I guess the time course he was in pretty right age for appendicitis again I tend to see it in kids who are a little bit on the younger side as opposed to an older teenager but he had a few preceding days of symptoms that were a little more nonspecific you know general GI complaint and then ended up having more localized pain and so I think taht fit the fact that it was a very accute episode made sense for appendicitis if it was something more like malrotation that's more chronic and then volvulus where you have the twisting of the intestines, that would be a little more episodic. Also thought about this being intussusception, that's more episodic, and wouldn't be more constant more progressive. So i think it fit more of the pathophysiology where you have some sort of obstruction or (???) went up with the appendix you start to develop more necrosis and gangrene and then perforation and it didn't look like he reached perforation point thankfully.

AP: And so how much were you considering that when you were in the diagnosis process? Versus just you were able to tell us now.

E: I mean I think weight what my next steps should be- does this make sense, does this time course fit, I think it does weigh in- I don't think you'd talk it out but it's something you go through like a mental checklist, like does this really fit, is this a common presentation of something uncommon, or is it a really an uncommon diagnosis.

CK: And what did his followup look like? After you made the diagnosis, can you tell us what happened to the patient after that?

E: Yeah so I talked to one of the pediatric surgeons at [place], and he transferred from one of our satellite sites in [place] to the main [place] and went to the OR that evening. So.

CK: And we were wondering if you could go back in time, is there anything you would have done differently when managing this patient?

E: Yeah, I mean maybe not having so much hesitation at the beginning, I just remembered it caused me a lot of angst, and. yeah. So we do handoffs- there's a daytime hospitalist and a nighttime hospitalist, and I think it kind of also clouds your vision if the nighttime person hadn't thought about it either, and

I'm trying to remember if it's the same nighttime person a couple days in a row. And it's just like Oh, you know he's doing fine he's just having a little abdominal pain, seems like gastro, just a little bit more prolonged. Kind of like an atypical presentation of gastro. And I think that kind of weighs into your judgment, I know for other cases where people have thought or have mentioned to me have you thought about X for these reasons, I think that's really helpful too, I think that helps you kind of take the blinders off and think more broadly, especially if you have certain blind spots for particular situations.

CK: So you talked a little about teamwork being a part of how you manage this patient. Are there other points during the course of your reasoning process or managing a patient or you felt like other people played a role in how you were thinking about the diagnosis either positively or kind of swaying you in a different direction.

E: yeah I mean I remember the nurses were concerned because our unit you know we don't we don't have an OR we don't have an ICU, we're pretty limited as a community site and so I think whenever there's a possibility of an appendicitis they want the kids transferred ASAP as opposed to do an initial work up and I think that's always kind of the tension but you know because he's older they can protocol the CT scan pretty easily cuz he's essentially an adult it's much easier study to do he doesn't need sedation so I feel like it would be faster for me to get the Imaging at [place] and then get that information and then transfer him over to [place] as opposed to trying to coordinate coordinated transfer and trying to get scans over at the main campus because then it becomes an issue of if we don't know if it's appendicitis I don't necessarily know if the surgeons would want to take them on to their service then we can go to General Pediatrics and then that's one hand off and then let's say he ultimately has appendicitis then does the surgery Team Takeover or do they consult and yeah sometimes it can get a little bit fuzzy and he was clinically stable and I think, you know, do we image now/a little bit later which team do they transferred to- I think those are all kind of considerations- but I guess I wish in hindsight I wish knowing that he had appendicitis I wish I imaged him sooner, I don't think that would have changed his outcome, but yeah. Not doubting myself too much.

CK: and how do you think a trainee at whatever stage of learning would have handled this case differently - like do you feel like there are certain parts where they would have not known how to think about the diagnosis as well?

E: Well I don't know if they wouldn't know how to handle the diagnosis. I think like on the flip side if it was - if I was the attending on blue team and he was on the teaching service, it might have been easier because you have more people to bounce ideas off of. And you know students and residents will come up with really great ideas that I may not have considered, and so I think when those come up then I'm like, okay well I have to actively disprove to myself and the team that it's not these additional diagnoses, or do we need to open that door and kind of investigate it. When you're attending by yourself, you know you're the only doctor on the team persay, then it's a little harder cause then it's an internal dialogue that you're having with yourself. And sometimes it's nice to bounce ideas off - and I'm sorry, I'm forgetting your question.

CK: Just whether you feel like there's a part in your reasoning process where you feel like trainees would have had a challenging time?

E: Yeah I think what I've seen is when to draw that line of this is just a prolonged course of this, and that's why they're not responding. That's just kind of this patient's natural course, it's a little bit more unusual. Or like oh no do we have the wrong diagnosis, and do we need to start from scratch? I think

knowing when to draw that line and I think it's really hard. And I wonder if that just comes with a little bit of time, experience, and coaching.

AP: How in this case did you decide when to draw that line?

E: I think when I was thinking about it more than - not that I should - but like where I'm like if I'm that worried about it where I'm doing abdominal exams like every half an hour to an hour. And I'm like I just need to bite the bullet and just do the imaging if I'm that concerned about it medically, or if I feel like he is just so tough that he's not going to tell me unless it's too late you know, and it's a huge question then just go ahead and do the imaging.

AP: What were critical decisions that you made during the encounter with that patient?

E: I think the critical decisions were I guess talking to the family, that you know we initially thought this was going on, but something is just not fitting. And kind of sharing okay this is also now what's on the table and what we're worried about. And then explaining to the family what the next steps would be. I think that was a critical piece where you kind of go down this one path where you're just like oh you know they're just in for IV hydration and some Tylenol for pain control and that's it. And then it's like wait we're not sure, you know that we had the correct diagnosis. And then how to do that in a way that doesn't undermine the other providers that had seen him earlier. You know and kind of explaining the nuances that again in the beginning the diagnosis of the stomach virus seems really reasonable, but these are the parts that don't quite fit. And this is why I think we need to look at other things, it might be for naught and it might just be a really bad gastro. But I think it's concerning enough that we need to look at different things. So I think having that conversation without saying, oh yeah the ER doctors should have probably just pushed to get a scan if the ultrasound was equivocal. I think there's a fine nuance, and sometimes families will ask was this missed, or what could have been done differently? And I think there's many ways to approach it. I tend to do something where you know if I'm not physically there and I wasn't taking care of the patient like with retrospect, it's easy to kind of point fingers and make judgments. But in the moment, everyone's doing their best, and everyone's well-trained and well intentioned. And they don't purposely try to miss things, or not do the right thing.

CK: Has this encounter with this particular patient changed at all how you think about clinical decision-making now?

E: I think the thing that it teaches you, a lot of these types of cases, is that kind of trust your gut instinct, and if something doesn't feel right, to pause and kind of reconsider. There's another case that's still really highly sensitive that I probably won't be able to share, but like I had a gut instinct that something wasn't right like through the course of you know about a year-and-a-half. And it was a total blind spot, but like trusting your gut instinct of if something doesn't feel right. And I had even paused and thought well does this really make sense? But then you kind of talked yourself out of it and knowing that was my blind spot, that there were other factors where I wasn't able to see it as clearly. But when you take a step back and look at the whole big picture, they're like way this completely makes sense now, and how did I not see it before. So I think trusting your gut instinct, pausing, which is hard because I feel like for the residents, for the students, for the attendings, the whole teams are kind of sometimes pushed to their max. Like you know efficiency is key, like you have to keep the hospital flow going. So I'm based in inpatient medicine, and you know the beds are really tight, you have new admissions coming in, you have all these other tasks, and the cognitive load is pretty high. Like how do you choose when and who - which patient to like stop, pause, and think okay what are we missing you know, like what are we not

getting. And what is kind of typical, the range of kind of what you would expect a typical course to be, and like what is kind of the outlier. I think that's also kind of an art that you learn over time.

CK: And so for you, how do you think you developed this gut instinct that you referred to?

E: Gosh, I think making a lot of mistakes. Making mistakes and knowing that when I didn't trust that something just didn't feel right - I don't know how else to put it, like something about the situation whether it's a social dynamic or just how sick or not sick the child looks, like something just doesn't fit. And a lot of times we want to have a diagnosis, and we want everything to be so neatly packaged that sometimes we'll ignore the things that don't fit and somehow try to make that square peg fit into the round hole. And it just doesn't work, so I don't know if I can describe. But it's just like are we are making too much of a snap judgment, are a lot of our biases - even for time of like trying to you know check this kid in, do the admission, get in the orders, and kind of be done and move onto the next patient. Yeah when are we moving too fast, and are we ignoring things because it's inconvenient.

AP: So this case that you just talked about was one that was more atypical. And so what's your decision-making process like when it's a more typical case?

E: So I think one of the classic things that we see is bronchiolitis. In the winter time, pretty much all the kids who have respiratory symptoms either have asthma or bronchiolitis. And I think for that one it's almost like the quick decision-making where it's like if they have the symptoms that are consistent with it, if they're in the right age group, and it kind of fits that illness script really neatly, then a lot of times I don't put much more thought into it. It's just more when their severity of illness is a lot more than I would expect, or it's a lot more prolonged, or there's just really unusual atypical features. But it's almost kind of that quick thinking and slow thinking - I'm forgetting, but something along those lines where you kind of just get into the repetition. Like nine times out of ten that'll serve you well, but I think there's just the rare kiddo where you know you're going to miss something, and it's not bronchiolitis but it's a foreign body that they aspirated and they happen to have a cold on top of it. But then in those situations, they're not going to respond as you would typically expect.

CK: How do you decide when you've had enough information gathered such that you can move forward with let's say a treatment or something else in terms of managing the patient?

E: Yeah, that's a good question. I think for certain things where the diagnosis is pretty clear, like let's say they have cellulitis, if you have a concern for osteomyelitis, certain infections where it's pretty straightforward. Then I feel like once you have a history that's consistent with it, you have enough of the data - I have blood cultures that are pending that will help me narrow my antibiotics if I'm able to get that information, then you just go ahead and start treatment. And as far as like monitoring for blood tests, I think even when I started around 2009, we were a lot more aggressive in terms of treatment for let's say osteomyelitis where kids would get PICC lines, we would monitor their labs pretty much daily, and do you know like long-term IV antibiotics. And I think over time we're learning how to do less safely, and then provide more value to the family. And so I think one of the things earlier coming out of training, I think you want to have all the information, and you want to know every possibility and rule out every single thing. And it's more of a comfort level where over time I've gotten more comfortable with not necessarily knowing all of the information, being okay with that ambiguity or uncertainty. If I don't know if that quite answers your question. Like even for croup, I would want to get the respiratory swab to prove that it was parainfluenza cause that's the most common virus that causes it. But now I'm like well if it's parainfluenza, we just spent I don't know a thousand plus dollars on this test, and does it

really help me? Not necessarily, sure different viruses might have a little bit of a different time frame but how much value is that going to provide the family.

Again some families might want to know but even if I have the virus and the typical span for how long it's going to cause symptoms, like every kid's different. And so how much that's going to offer them, I'm not sure. I think - it's still pretty controversial, and I think other people might have very different opinions of like if you know it's this virus, then you know it's going to be this many days, you know what the course is. But I'm like yeah but you're still not taking into account the patient, and then it matters more for the patient like even if 99% of the time it'll be resolved by 7 days, if that kids at 1% then it doesn't matter for the family, it's 100% for them. And I think being comfortable with a little bit of ambiguity and being open to families about it - cases that I think about in that situation are kids who get referred from outside providers or other hospitals because there's - things are still not quite diagnosed, and they've had like a million dollar workup. And kind of where do you go from there, and how much do you do, and how many answers do you have? And I think in those situations we try to be honest with the family that we might not have all the answers, we likely won't have a diagnosis at the time of discharge, but we want to exclude you know the things that are really dangerous that we would need to treat immediately, and kind of have that. Some of the tests we might do won't come back for weeks, and you know we're not going to keep you here in the hospital for weeks, like it's to no one's benefit. But really trying to be open with the expectation.

I think the tricky one where I think about how certain do you have to be before starting treatment, the one is Kawasaki disease. And so it's tricky because there's generic clinical criteria, you know it's like fever for at least 5 days, and then you have like certain clinical features like four out of five clinical symptoms for classic, and then you have two or three with supporting live data for incomplete Kawasaki's. But there's no like diagnostic gold standard tests where like yes you're tested positive for like strep throat. But then you generally have a window of 10 days where you want to treat to really optimize your treatment to prevent the cardiac complications, and so in that case, if a kiddo's getting toward that 8/9/10 day mark, and they come into the hospital. Then at that point, sometimes we'll do the basic lab testing to look for other viruses, like other titers. But then you know I would go ahead and treat because if I have that clinical suspicion, I'm probably treating kids unnecessarily but I'm not really comfortable taking that risk if I miss Kawasaki's and they have heart complications like coronary disease. You know the risk of IV Ig and aspirin - you know there are risks involved, but I usually counsel families like - I try to walk them through kind of our thought process and really being open and honest about it, like this is the most likely diagnosis, again it's really rare but the complications are really severe, and there isn't a perfect test for it. And so we often will over treat kids knowing that and being really open and honest about that, saying what the side effects are. And then even saying that you know again this diagnosis is pretty nebulous, and sometimes when kids have recurrences then we have to revisit and say is this a really unusual case of Kawasaki's, or is there another vasculitis, another rheumatologic condition, that we need to consider. Again it's pretty unsatisfying for families because they're like well why don't you have a test. And then it's a whole other discussion. So you don't know what causes it, you don't have a test for it, you give these two medications, and you don't really know how or why it works, and so like what is happening, and it's a hard sell. But I think when you frame it as these number of kids will go on to develop cardiac complications, and we know after the fact, you know then I think most families are reasonable and pretty open to treatment. But that's where I work on completely incomplete information, and you do the best you can. And I think trying to be open and honest with the families to try to get them on the same page.

CK: So you mentioned that when you first started out that it was harder for you to deal with that sort of uncertainty, and now years later, you feel like you're more comfortable with making those decisions than early on. What do you think helped you make that change?

E: One of the things I guess for the frequent lab tests - so when kids are on IV fluids a lot of times the dogma when I was training was that you'd get electrolytes every day to make sure that the salt balance was fine. But then after a while you do it, and then you have a bunch of normal tests. And then you're like okay why I'm doing this, and I'm proving to myself that it's normal test. Or you know the kids with croup, I get the swab, it's parainfluenza, does it change anything? Does it help the family? No, so then why am I doing this? This is not only going to change my management of what I'm going to do, but does this help the family or child in anyway. And so I think over time I got used to that. I think one of the other benefits of being in the hospital is I have the luxury of time. And so I'm able to see how a child does, as opposed to you know being in the outpatient setting, it's a lot harder. Because you know you send the child and family out into the you know ether, do they have access to care, would they have the comfort in recognizing when something is getting worse and the ability to come seek care. And so I think that makes it a lot harder for outpatient doctor's because they don't have that luxury, whereas I have kind of a captive audience, like okay so they had a fever, they don't have a central line, they don't have other risk factors, you know we could watch them with a fever, but if they look - so let's say two hours later, they're rigoring and their blood pressure is getting a little bit soft, they're tachycardic and looking a lot sicker. Well then we can use that information and then intervene, but I have the luxury of time I think also helps.

AP: Maybe you can think back to the appendicitis case or just in general, are there cases where you need to acquire new knowledge or skills in order to move forward with the case?

E: Yeah, I'm trying to think of... [pause] I think there's always opportunities to gain more knowledge. I'm trying to think of, do I do that in the form of consultants, so I think that's one avenue. Oh! There was another kiddo who we took care of. We ended up consulting GI. So she's a teenager, totally healthy, came in with what sounded like gastro and passed something that looked kind of like a worm in her stool. And so we were - and she had eosinophilia. So we were really anchored on you know, is it some sort of parasitic disease? And so she had I think one ova and parasite that was negative. And so we did a couple more, and those were negative. We talked to Infectious Disease to see if there was anything else. Cause I was like really fascinated, she loves to eat sashimi, and she likes to eat salmon, and if it's not prepared properly you can definitely get parasites. And then this that she passed, too bad that she flushed it. But they took a picture of it, and it looks kind of like a worm. So we asked ID, and they didn't think it was the case. And she continued having diarrhea and would have a lot of vomiting every time she tried to eat, even though she had a good appetite. So we ended up involving GI. We were waiting for some of the stool studies to come back, and then they ended up doing an endoscopy, because it was just atypical for them. I think she was sick for about two and a half, two weeks when I had met her. And when the attending took over for me the week later she was still having symptoms, I think we had started her on PPN to give her some nutrition cause she wasn't able to take anything. And then she was diagnosed with eosinophilic gastritis, and so it's an entity that I'm not as familiar with and so having to learn about that. So definitely opportunities, I think we usually use consultants to say ok this is what we've thought about, this is what I'm worried about, this is what I think we'd want to do, and you know does she need additional imaging, does she need additional evaluation like a scope. So I think that's one way, I think usually consultants.

CK: How do you decide in your clinical decision-making process when it's time to bring in a consultant?

E: Yeah, and so I think it's when I have a very specific question for them. And so again there's a wide spectrum of how people do consults. I guess it depends on a couple of things, depending on acuity. So if a patient's really acutely ill and we need help right away, then we may have a partially formulated question or might be a very generic question, like you know we're concerned about this patient with septic shock, they've been on broad spectrum antibiotics, what is our gap? What are we missing, and what do we also need to cover? And then additional emergent imaging that we would need to do. Like I would call ID for that like very urgently, it's not a very sophisticated question. Or is it something a little bit less urgent where you know we could start our initial work up and then if the common things that we would generally think of as a generalist don't pan out, then at that point I think talking to other consultants. But I really try to push the residents to have a specific question. And so there's a new movement, one of the neurology residents - peds neurology residents is working on a project of how to call a good consult. And so they use kind of the SBAR format, so Situation, is it emergent or urgent, or kind of routine. What is your specific question? And so that's your situation. B is for background. So the one-line description of the patient, what their symptoms are, what workup's been done, kind of your assessment, like what we had as a primary care team are thinking about and the recommendations of what we would want to do if we didn't have this particular consultant available to us.

You know there was one patient where they came back with - he's had chronic pressure ulcers for about a year and like really bad ulcers, he has hardware in his spine, and some of the hardware was exposed, and ended up coming back with a wound culture with enterobacter. Totally clinically stable, I mean he's had these infections for a long time I'm assuming and went in for debridement, and then happened to have that wound culture. Because he was clinically stable, we talked to Infectious Disease. It was a routine consult because I was planning on changing the antibiotics anyway, but you know - I remembered to make it more of a teaching opportunity for the residents because I think the culture came back I think around 4 in the afternoon. On the note, I remember putting in like, consult ID regarding specific layer question of number one do we change our antibiotics because enterobacter has a potential inducible resistance, he's currently on ceftriaxone, do we need to go to cefepime? That was my first question. Number two, do we still need to consider a polymicrobial infection, just given the location and that he's diapered, because right now we're really focused on gram-negatives. And then the third question is like duration of therapy given that it's a chronic osteo, cause it's not going to be like your standard osteo. And then like do we need to do suppressive therapy, do we need to do other imaging to look for surgical debridement, or to decrease the surgical - or to decrease the actual burden of the physical disease of the bone being infected or tissue being infected. And so I remember typing that out to role model for the residents of like you know what kind of questions I would want them to ask, and then when ID is doing his chart review, cause he'd been there for a while, so then they knew what to focus on. Like were we worried about his past history of MRSA pneumonia, yeah not really cause that seems like it's kind of done and over with. But this was my specific question. And then I think it helps to target their discussion, and then if the team puts forward their plan, then it's a more active discussion. They're like, oh you know I wouldn't change it to this, I would change it to this for this reason. But if you say, ok ID consult for an infection, then it's really nebulous. And then they'll say, okay well do these imaging, get these labs, and start this antibiotic. And there's no real dialogue, where I feel like it's a huge lost opportunity to kind of understand.

CK: And going back a little bit to the lymphoma patient that you mentioned. I'm curious so with the appendicitis patient it sounds like you were the one who was interacting with him from the very beginning. So with the lymphoma patient, it sounded like it was a little bit different because there was some information provided by previous providers. And I was wondering if you could tell us a little bit

about how your clinical decision-making process changes, or certain factors that you keep in mind when you are receiving a patient who has already been seen by other providers?

E: Yeah I think in his situation I learned so much from his particular case, and so there were a couple of red flags just going back and talking to the family and in his history. I think just the acuity of how quickly he got better and how quickly he worsened the minute the steroids came off. I think that was the huge learning point like that's one red flag. He wasn't able to lie down, he had orthopnea and so he had to sleep with two pillows because he had this mass that was compressing, so every time he'd lie back, it would compress his airway even more. So that was a second one. And then the third one was he had all these bumps in between his rib cage, and it wasn't where lymph nodes are. And so I kept wondering like what are these little blobs cause they feel firm like lymph nodes, but there's nothing there like is it skin infiltration of leukemia or what is going on. And then we ended up doing a CT scan of his chest, and he had such huge pleural effusions related to his lymphoma that the pleural effusion - the pleura and the fluid was popping up in between his ribs and that was causing the blobs. And then learning that you know, in these patients with anterior mediastinal masses, that you know the compression that it causes is usually below the carina. So even if you try to intubate, if you lose their airway, you probably won't be able to get - to bypass that. And so to not use certain medications, to be really careful with any sort of opioids or benzos and making sure they're in the ICU having a contingency plan, if he has distress to put him prone to kind of relieve some of that, and so I think there were a lot of learning points. And then you know when I talk to the residents or students, then go through like cases of you know a five-year-old with wheezing. And again it could be a wide range of things to have those teaching points, like these are red flags that you need to really consider and think more carefully about - that are not typical presentation of asthma or pneumonia.

CK: So how do you approach information that's provided to you by another expert, by another clinical expert, who's maybe handing off a patient to you, or maybe they've been seen in a different healthcare system. But how do you approach the information that's given to you by that other expert?

E: So you definitely take that information in, but I think it's one of those things - it's kind of a little bit of paranoia. You confirm it and verify the information, and so even circling back with the families. So my understanding is that this and this and this happened, the thought was that this might have been going on you know. Do I have it correct or where am I missing the information? And I think a lot of that's helped by the way that we do rounds. We do rounds with the families present, and so we'll talk about you know overnight this and this happened. So then the parent will say, oh no well actually it was this one came first, and then this one didn't happen until hours later, they actually weren't really close in time. So that gets clarification of what might have been missed or misunderstood during that handoff process cause I feel like that's when patients are incredibly vulnerable. And so that's kind of a safety measure that we have patients or families who can kind of verify that information. But I think it's important to try to take that history even though we know a lot of the information, but more to verify. And there's a wide range of doing that, I think there's kind of an art to it, especially for the kids are really complex where the family is like, I just told our pediatrician, I just told the ER, and now I'm telling you again like don't you guys talk to each other. And I'm like yes, we do talk to each other but then I make it more targeted. And so I'll print out the last clinic note or discharge summary, and then instead of having the family recall all the meds you know off the top of their head, I'll say here's the med list that I have, is this still the same? And then we just compare it and then usually they're pretty savvy enough to know that we're doing that as a safety measure. If not, then we explain it but usually the families understand that piece of it. But I don't go through like so you know what medical problems do you have if they have like a bunch. You know if it's a lot of old stuff that we can find you know usually we can say, you know

we know that you've been - you know you have this, that you're being followed by this and this subspecialist, this and this. And kind of just more like I did my homework, so I don't want - I want to be respectful of your time, but anything that I got that was incorrect you know. And so and then having them fill in the gaps, and even kind of summarize so what my understanding was from what the ER docs told me is that this is what's been going on, it's been going on for this many days, and then sometimes I'll even have them take me back in like okay so you said that it started 5 days ago, so what was the first thing that you noticed? So even phrasing it in a little bit different way, so it's not like they have to tell someone all over again.

But again each family is different, but I feel like if I have frame it that way, like this is my understanding let me just double check a few things, then they're a lot more open than to like so what brought you to the hospital? [laughs] then it's like you guys don't communicate.

CK: I'll check the time real quick - oh ok, we're doing fine. I just wanted to make sure. I was wondering how you taking into account information from all these difference sources? So you have the patient themselves, the patient's family, you have different healthcare providers. And at what point do you prioritize these different sources in terms of how you're thinking through your diagnostic process?

E: Yeah I mean we take in all of the information, and at a certain point you have to trust the people that you're working and trust the family. And so, yeah I try my best to trust my team, and so I won't go in and repeat you know ask them the same history questions. I think only key things where I really want to double check if something doesn't make sense, but yeah it's tough, especially when you're working with many different levels. It's hard, I think yeah, I think it's kind of a balance. But if something doesn't make sense, then I think that's when what kind of re-clarify. And then I'll ask more specific questions like, you know how was the temperature taken for the fever? Ws it taken orally, was it taken rectally, and then probe a little bit deeper. And then some of the information will become a little bit more clear. But I try to assume best intentions that everyone is trying their best, that they're not trying to hide, and knowing that we all forget to ask questions and that is not a fault. You know if I ask oh so do they have any travel history? And you're like oh I don't know. I'm like that's fine, like we can ask together, you can go and ask them and let me know. And then you can kind of coach like this is how I might phrase it, or yeah.

CK: What's your approach when you have data that conflicts with each other? And this could be data broadly, either from different people giving you different information, or like different test results that don't quite cohesively all fit together.

E: I guess when different information - like let's say a nurse is telling me something and then the resident is telling me something differently, trying to get everyone in the same spot, and then say okay so it sounds like there's a couple of things going on, can we just talk about like what everyone's understanding, to kind of get all the key stakeholders. And I think that helps to clarify certain things. But if the data is conflicting - do you mean like across different healthcare systems, or just within...

CK: I was imagining like let's say if you're getting results of blood tests or other things like that, and it's not quite fitting with what you had in mind - whether it's your leading diagnosis or the illness script that you had in mind. How do you go about managing that?

E: Yeah I think it's another time when you pause. You're like okay does this make sense, you know am I missing something, what am I not considering. Yeah there is a particular situation, again it was hard cause it wasn't a true physiologic thing but there is a patient where they didn't have elevated inflammatory markers in the setting of what looked like sepsis. Again this situation is a little bit unusual,

but one we have often. I'm like, well by all means and purposes it looks like it's sepsis. For a variety of reasons, I think the patient may not have an inflammatory response yet, let's check the results again in 24 hours and kind of see where we're at. Because I anticipate we'll have positive blood cultures, and we'll have to repeat blood cultures anyway, so we have to go into her central line so it's not an additional risk factor for causing a nosocomial infection. Let's check labs, and then at that point the labs became abnormal. And so I mean there's other reasons why they were normal in the beginning but yeah. Like do you retest? And then for that other patient - with the teenager where I was concerned about the parasite. She had the three negative o&p, and my colleague who took care of her after, he looked up a paper like you know is 3 o&p's enough? And the sensitivity is actually really good, and at that point we're like okay we've gotta move on from this parasite, as tantalizing and exciting as that would have been. Then we need to involve GI, we need to think of other things, because clearly the negative test is probably a true negative and not something that we're missing. So I think do you repeat the test and see if it helps to kind of fit what your working diagnosis is, or is that when you kind of re-evaluate what your working diagnosis.

CK: So in terms of thinking about clinical reasoning just broadly for students who are learning, have you noticed your students particular struggle with particular steps during their training?

E: Thinking preclinical or clinical students?

CK: Maybe we can start with preclinical and then go to clinical if that makes sense?

E: Yeah, I think - it's interesting because the [course] cases have recently changed, which makes it kind of fun. So before I felt like the cases were pretty classic, very kind of typical cases, like very scripted for the typical illness scripts, like very textbook cases. Which makes it kind of nice and clean for teaching, but I kind of like the ambiguity in like not knowing, and where there's no right or wrong way to do it, cause I feel like that's a much more interesting discussion as opposed to, okay these are all that you know - like nine out of the ten risk factors for endocarditis and yes the patient has fever and has endocarditis. Like woohoo, like we got it - but it's pretty clear. As opposed to one where we're like, huh what would we do? Like the labs don't quite fit, like where do we go from here, I think that's much more interesting and I feel like it's more true to life. So the prior cases - again I've only done [course] since 2013 - but up until this year it's been very classic. And this year it's been very ambiguous, and for the second years I don't know if it's too early for them, where they kind of struggle and they're like, but it's so vague, and how do you know or not know, and what's the right answer cause we want the right answer. But I think it prepares - I hope it better prepares them for the wards because I mean very rarely is there ever a straightforward case where it's a classic whatever. Especially if they're seeing patients at adult [location] or at [location] where it's not the typical cases. And I think pushing them, like having the ambiguity kind of pushes them to really justify like how comfortable are you? Like would you really treat them? Would you do more tests? How would you prioritize your test? And then I think it's more fun to get them to commit to it. Again I don't know if it's kind of too early where they just need something like very neatly packaged to kind of get a sense of it.

CK: And then with clinical students?

E: With clinical students and even residents, I think they struggle with the ambiguity. And I think not knowing, not having a diagnosis for the kid who come in with the referral, they want to do every possible test under the sun. And then yeah I'm like, I don't think we're going to have a diagnosis and that's okay because we've ruled out the dangerous things, we don't have leukemia, we don't have x, y,

and z. I think the other part where people - I don't know if it's really the clinical reasoning piece of it, but having a gold standard treatment, having like a guideline. Because we have certain guidelines, but a lot of our patients are complex. And there isn't a guideline, and I feel like there's a lot of discomfort with that ambiguity. I think it takes a lot of coaching and walking through the steps of - and being really transparent of okay there's no right or wrong reason. This is kind of the art of medicine, it's very stylistic, these are our two options, and this is what I'm weighing pro and con for each of them, and this is why I'm leaning more towards this. And having that discussion openly, as opposed to like magically choosing option b when there's you know equipoise between the two.

CK: What helps you decide you know choosing between a couple options if there's no specific test, or gold standard way that you would be able to decide, what other factors do you use to decide which one to go for ultimately?

E: This is a huge waiver of mine. I think shared decision-making I think is a prime opportunity to be utilized in those situations where there's no clear guidelines, you really want to involve the patient family, the caregivers, with their preferences, their values of what's important to them. And again, cause if there's no right or wrong way to do it, then I think making sure that we have the family way in, is hugely important and being respectful of their values. Again shared decision-making I think is fantastic, but for certain things, like if there's gold standards you don't want to provide options when there aren't really options. Like if there's someone in sepsis, I'm not going to ask them do you want epinephrine or norepinephrine, how fast do you want to run the drips, like that's not an option. But other things I think there's a lot to be considered, and I think that's kind of changed over time. I think in the past it's been very paternalistic where you know the medical team prescribes a therapy, and it's kind of just how it's done. And I think we're shifting more toward family-centered care. Again we don't want it - I worry if it becomes family-driven care, where the medical team just doesn't have any input. But I think it's a partnership in that families - if they're interested in being involved

CK: And what kind of family or patient values do you find come up most often when you're deciding between treatment options?

E: I think how comfortable they feel with giving certain medications, or like if they want - I mean the simplest one is like do you want to take a pill or do you want to take a liquid? I think that's kind of the easiest, lowest hanging food. Or do you prefer an inhaler, do you prefer a nebulizer? And again I try to propose like this is why I think this option would be really good, but again I want to be respectful of - cause if the family isn't able to adhere to it for whatever reason, then you know it's kind of pointless. And so I'm trying to get their buy-in. But you were asking about other kind of decisions that would lend itself to it?

CK: Yeah no, that covered it. I guess I was just - you mentioned that there were family values or family considerations that you would take into account. But that gave me a sense for what kind of ideas that you had in mind.

AP: So thinking way generally, what do you think differentiates an expert clinical decision-maker from a less expert?

E: I think it's hard because I don't consider myself to be an expert, like I said in my email [laughs]. I think we're all learning, and I think it's really important to know what your limits are, and being able to say I don't know and I need help. I don't know if that makes you expert or not expert, but I think it makes you a better doctor, better educator to do that, especially in a lot of my teaching sessions I mean as a

pediatrician, the cases are a lot more Internal Medicine heavy so many times, I don't know. I don't deal with this type of medication, or this type of situation, and being open and honest about it. And then saying okay but these are ways that we can figure it out, or resources that you can use to look at that information. But I think being open to that and not being so dogmatic about a lot of things, I think is helpful. I think keeping an open mind and a real growth mindset, that just because I don't know the answer doesn't mean that I'm a bad doctor. Just because I missed this doesn't mean that I'm a bad doctor. I think we'll all make mistakes, it's just how it works, and how life works. But I think the ability to be able to stop and reflect on it, and what could have I done different, and how can I learn from it, I think is really valuable and provides a lot of insight. And it's part of that lifelong learning process, like I don't want to make that mistake again.

CK: Can you speak a little bit more about that reflection process?

E: Yeah, I mean I think it's kind of an ongoing dialogue that's running throughout your head. So you know it's not necessarily like at the end of the day I reflect on everything, but it's more in the moment I'm like, oh you know that encounter went a lot easier than I expected, okay what went easier, how did that happen, like you know what was I preparing myself for, kind of putting up my guard for. Or that went a lot worse than I expected, and a lot of times we'll debrief with the residents or the team, and go like ok so that didn't really go as expected, so what did you guys think happened? You know what do you think went well, what was challenging, what was unexpected, and I think having that reflection is important. A lot of times we do it when things go badly, I think we should do it more when things go well. But that reflection can be important as doing that as a team, as role modeling, but pretty much like every encounter I'm like, oh how did that go. But it's not something that like I would necessarily journal or write down. Although I'm trying to do a little bit more of that type of journaling, but yeah thinking about okay, why did that not go as well, or if it sits kind of funny with me, then I'm like okay what could I have done differently. And it's just a constant thing, it's not like you know every Friday I have that reflection, but it's really an ongoing dialogue

AP: It looks like it's been an hour - we don't want to take too much of your time!
CK: Thank you so much!

E: I hope it was helpful!

Medical faculty 2 (internal medicine)

C: So the point of this study is to get a sense for how expert clinicians really go through their diagnostic process and so we want to start off with a question of having you think of a patient case that you feel like best represents your clinical reasoning process. And then if you can tell us step by step the actions that you took with this patient, conversation or anything else, from the moment that the patient came in through the door.

Ok. Alright. Yea. This happens a lot with clinics. I can just think of this week a patient. So this is a common scenario actually. Patient comes in with urinary frequency, just urinating a lot. And I treat a lot of veterans at the [place]. Elderly men obviously and so you know the typical approach is that to think of a broad differential and a framework that you're thinking of with respect to polyuria. And so in this age category obviously you think of the common things but you also want to be broad so you don't miss things. And that allows you to think about questions that you should ask to narrow things down quickly. And so in a broad category like this you know in elderly men the things you think about are obviously prostate obstruction or obstruction from other causes that might cause them to urinate a lot. And of course they're at risk for diabetes so things like you know endocrine causes that might do this so that's another. And so you sort of have these big buckets of things to think about and then within those you want to ask the questions to kind of narrow things down.

C: If you can give us some details maybe about what kind of specific categories you're thinking about?

A: So think about one specific thing and walk us through.

C: So I think the polyuria case is great example. And if you can walk us through the details that you were thinking through.

Yea, so this guy I'm trying to think who came in last week was actually having also some pain with urination. He didn't actually come up with that right away. His main concern was that he was urinating a lot and so some of the questions were you know are you urinating large amounts or are you urinating small amounts. And so he was urinating small amounts frequently and then yea there's a little bit of pain and so that takes me down the more likely infection but it could also be two things. He could have enlarged prostate and an infection. And so then you have to narrow it down more through examination obviously of the prostate . Could he also have an infection of the prostate and an enlarged prostate. So it ended up that he did have a prostatitis. So he ended up having a tender prostate and a large prostate and pyuria. So he had a UTI in addition to large prostate which probably contributed to the UTI and so that's the case that I was just thinking of.

C: What do you feel like were the critical steps that you made in order to come to that diagnosis?

Well thinking of the background of the patient, you know staying broad also initially and then asking the right question to sort of narrow things down and then thinking of what are the key exam points that I need to do to sort of verify the diagnosis to what key studies we need to do in clinic. Yea so we ended up doing you know an ultrasound in clinic to look at his bladder to see if he's retaining urine, eye exam, obviously vitals, abdominal exam and then the studies you know urinalysis, blood count, yea.

C: And so when we think about the questions that you're asking, can you walk us through some examples?

Yea. So initially you're just looking at him to see if he looks really sick and he didn't. So that's kind of a good start in some ways because if he was septic from you know a urinary tract information like pyelo that would change my rapidity of what I needed to do and things like that. But he looked ok. And then asking him other questions about like I said how much he's urinating you know is he also having dry mouth which makes me think that maybe he's having high glucose. Vitals obviously very important because that can change things if he's sick. And then questions around you know, infection. Does he have pain when he urinates, does he have fevers, has he had back pain, has he had change in color of the urine. So that you know led me down to an obstructive problem, he was having nocturia. He was having small amounts of urine and he was having urinary frequency so that led me down to the exam and I can focus in on prostate exam, abdominal exam and then we did a bladderal urine analysis, finger stick glucose and so yea.

A: So trying to get a sense of the order of things you started with asking those whole set of questions? Did you and then you do the exam and then you do the labs? Or what's the?

Yea, it's just a systematic approach and you know I can see myself maybe going a little different direction if other answers were given to me. But you know as you sort of rule out sort of these other things like he wasn't having the dry mouth. You know you got the fact that he has pain so it's probably less likely he has diabetes. He didn't have diabetes history although he was somewhat obese guy so he has risk for that. So the questions sort of lead you down a certain way.

C: And were these buckets as you call categories things you had sort of already pre-thought about before coming in or was it something that you started developing as you were talking?

Yea, there's sort of pre that I already kind of have as sort of my framework when I think about this and then when you see the patient obviously then that framework comes to mind to where you're using it on that patient especially with that background. Now it could have been a lot different if the patient was a known diabetic for example you know. Or if I'd known that they were on medication or if he's a heart failure patient for example right then you think maybe this is his diuretic sort of things like that or yea. So the background of the patient might help and then yea.

C: Can you tell us a little bit more about the follow up tests that you did with the patient and how decided to choose those specific tests?

Ok. Yea so those came to mind obviously with the fact that he had the pain with urination and the prostate was tender and then that leads me down to let's do the UA right there in clinic. Let's do a finger stick just to make sure let's prioritize getting us some antibiotics because we suspected that the urine was going to be positive based on my exam of the prostate. So actually probably getting antibiotics even before the UA is back because it takes a couple of hours to get that back. And then of course that confirms it and if you know he already gets the antibiotics and get started on that that day instead of waiting calling in the afternoon maybe.

C: So for empirically providing antibiotics to him, at what point did you feel like you had enough information to go ahead and make that kind of decision?

Yea I think after the tender prostate that kind of closed it for me. You know I think in other cases where it might not have been like a prostatitis if it was more of a simple UTI like a cystitis you'll often not get a physical exam findings and you know it's not as severe so you can probably wait until you get the UA back. A couple of hours is not going to make a difference. I mean frankly it probably will not make a

difference with prostatitis either but the fact that it was tender there's not many other things that can do with a tender prostate with those symptoms so I felt comfortable that we crossed the line.

C: And when you think back to this case was there a particular piece of information that you felt like the patient gave you that really set how you were thinking about the diagnosis?

Yea, the pain with urination. Even though it was subtle you know it's that kind of hedges you that way and then you get the tender prostate you know. I think maybe it's not just one thing but it's those two things and you're like oh this is really pretty much likely it even though he wasn't having a fever. You know you can only diagnose people with fever. So you sort of not throw out things but you realize that in reality a person with prostatitis may not have a fever so you learn by experience that certain pieces of information are valuable and also you take some with a grain of salt.

C: Can you tell us more about the things that you take with a grain of salt?

Yea so like I said in elderly person or if a person had immune suppression certain conditions aren't necessarily systemic like a prostatitis or a local UTI doesn't mean you're going to have a fever.

C: Was there anything that stood out as unusual to you from this case?

Yea the fact that he didn't that his chief complaint wasn't pain with urination you know. So it kinda throws you. But I don't know I've seen that even though that's typically the like the never one chief complaint in a patient with UTI. Elderly people may not have that or think it's no big deal. They have a little pain you know it's something they kind of unless you really ask them and probe you may not get it.

C: Do you think there's something maybe unique about the population you work with that changes how you interact with them?

Yea definitely the elderly I don't know the veterans tend to be more stoic so I've seen guys with chest pain that have actually had like aortic dissection that will drive 3 hours and think I'll make it to the ER instead of going to the nearest ER. You know they're just real stoic you've been through the war, yea a little pain with urination it's no big deal, but I'm going a lot, it's really making me stay up at night, it's kind of bothering my sleep. But then the pain with urination is like it's not a big deal. Yea if it was me I would probably be complaining. So yea for my population there's things you learn with experience.

C: And does that change the kind of questions that you ask them or how you think about the diagnosis?

Yea. You have to ask directly like I remember me as an early faculty I would ask anything in pain or anything bothering you and they'll say no. Unless you ask do you really think about like when you urinate do you have any pain you have to be specific. And they'll be like oh yea that actually does hurt a little bit does tingle or sting.

C: yea then you have to kind of shift tight to think about it.

Yea you have to like ask a general questions and then be more specific. Do you have pain when you urinate?

C: And thinking about the specific case you told us about, I think with the gentleman last week that you saw, was there any information that you collected that you felt like didn't actually align super well with the working diagnosis that you were considering.

Yea, I guess no fever. That was probably it. He didn't really have any abdominal pain either. Usually people have a little bit of that. The fact that like I said the question initially didn't come up with pain in urination you know it's a little unusual. But also just the fact that this is a diagnosis that you don't want to miss and it's not that uncommon for elderly men.

C: So how do you decide whether information that doesn't fit with your working diagnosis is big enough to change your working diagnosis versus enough that it's sort of a person to person fluctuation.

Yea so one you don't want to miss and then like I said in patient's population they may not have it based on immunosuppression, age, and being stoic. You know things like that you just realize that patient population may be a little different.

A: So I'm wondering about it seems like this was a pretty fairly routine case.

Yes.

A: I'm wondering if there's a challenging case that you can think about that you can walk us through as well just so we get a little bit of diversity.

C: Or maybe one that you felt like really pushed you with your clinical reasoning?

Oh yea. No definitely. There's some I can think of that are very challenging. So it's the ones that sort of take more time to figure out cause it's over not just in clinic and you sort of figure out when you get the test and the result. It's ones that might be rarer that you might see them for weeks and you might even have to get consultation and run the case by people. And so there's one that I can think of. This was a while ago but if I can remember right. This was a gentleman that ended up presenting with Eaton Lambert syndrome. This is a pretty rare condition that's related to often some cancer, could be lung cancer. And they present with its like a myasthenia gravis and so they present with fatigue. And fatigue is really broad as you know it can be just about any organ system cause fatigue right. From metabolic issues to neurologic issues to muscular skeletal issues to psychiatric issues. And so in that case you have a lot of buckets of things to think about. And you go kind of what's most likely in your patient population. You have an elderly guy who has history of cancer and fatigue and the first thing that jumps to mind is you know the cancer is recurring you know or there is something related to electrolytes you know because they're not eating right. They're not getting enough nutrition. And it just was really challenging because no he's eating ok and the questioning and the cancer has been treated and it looks like its stable it's not growing. So that requires a lot of steps and tests that you get back and then you're sort of having that framework in your mind. And all the ones that are kind of common that you kind of pick off first because you can't just blanket order tests at everything that would just be crazy you know right? So you're sort of then going back to the drawing board each time in your framework and said you kind of covered the common things and based on the patient's background. And then you're like well ok then you're going to more rare things and you're even bringing them back to clinic to maybe examining them more carefully in certain areas cause at first your diagnostic framework is not only based on what's most likely but it's also what you don't want to miss. Right? Cause those might be more prioritized in your testing so my initial testing clearly wasn't the eaton lambert syndrome because that's pretty rare and the tests to do on that are complicated because you gotta check for antibodies to this

receptors you know and those tests take weeks to come back. And so I think after the maybe 2nd or 3rd visit and I've been seeing him closely over weeks like I'd see him within a week and then within a week again. We're not getting anywhere and finally you know thinking what could this be you know this rare condition of eaton lambert syndrome and I thought about well and I had to actually look some tests up and think about neurological exams. I've done a basic neurologic exam on him but you can do a more detailed one where you actually check for fatigue and look at reflexes and it turns out that he was fatiguing with using the muscles a lot because what happens is they get antibody to this acetylcholine receptor and you have to do kind of a more detailed exam and it's like wow this is positive this could be it. It's not an exam that you do a lot right so it's one it's not an exam that I do a lot and two it's a rare condition. And then you sort of question yourself, did I do the exam right. Because this is not something that I do a lot. So when you see a positive findings, could I just be convincing myself that I'm actually finding this because I haven't found anything else. And then you order the antibody test and a week later it comes back and you're like wow. This is a really rare diagnosis. Took me probably 3-4 weeks to figure it out. But I had a lot of other you know parts of my differential that I exhausted before getting there. So I don't know.

C: So when you think about that case, what do you feel like was the critical decision that you've made that ultimately lead you to come that you did the right diagnosis.

Yea it's like I said ruling out things that I didn't want to miss. I think I was looking even at silent ischemia so we ended up getting a cardiac perfusion scan because he had risk for coronary disease. So I think after I felt like I've exhausted some of the common things and I was scratching my head that we weren't getting there and he was still really fatigued and these are stoic guys that generally don't complain. I felt like there was something really severe going on. This guy wasn't depressed, he wasn't malingering, he wasn't you know. This was something really real, probably neurologic. After examining a couple of times and then I think that critical exam point of the neurologic exam testing for fatigue was probably what did it for me. Yea that was probably it.

C: How did you think of doing the fatigue test at that point?

It was actually a reading. I remember actually thinking of all the my diagnostic framework and each of these and thinking it's gotta be something neurologic. I said what could be neurologic and I remember going to literature and then saying let's try this let's bring him back in to try.

C: What really tipped you off that it was neurologic?

I think because of the severity and the fact that it was getting worse with time and he was really weak. And then I think that he was saying you know it was actually worse when he was like after exercising. I initially thought maybe the fatigue with exercising was something vascular or cardiac but I already ruled that out. This has gotta be something neurologic or muscular you know related to that. He was having muscle tenderness and his CPKs were normal.

C: What kind of tests did you use to make your diagnosis?

Yea that was the antibody test.

C: And before you thought of getting the antibody test it sounded like you did several other tests beforehand?

Yea we did like a CPK, we did cardiac perfusion scan, and basic lab tests like potassium because you know, electrolyte abnormalities, calcium could do it, hypercalcemia. You know renal function, liver function which can cause fatigue. You know obviously screening for depression and things that was done early on cause you definitely don't want to miss that. Someone is depressed and suicidal obviously. A guy with cancer you're going to look at if his cancer is stable.

C: Was there a point during the diagnostic process that you ended up using your basic biology knowledge or something more pathophysiology?

Yea I think that's at the point of when the question of eaton lambert you're thinking is this guy with lung cancer I was thinking back and my internal medicine training. This is a rare disease that you can sometime see and thinking of a mechanism saying yea I vaguely remember that there is an antibody test for this and let me look this up. And actually I consulted neuro but you know the way things work is you don't you can't get them in right away so you gotta wait a few weeks. I said there's this guy I don't want him to wait a few weeks to get seen by a specialist.

C: How did you decide to reach out to neuro?

Once I was pretty sure that this was the diagnosis and I already ordered the antibody test. But before that I wasn't really sure and you'd hate to send someone to consult and you're still not even sure what category it's in. It can be cardiac you know and I don't know that if I were to set the consult earlier that would have made a difference. I mean I could have at the initial part I could have consulted neuro, endocrine, and cardiology just cause it could have been a lot of those categories.

C: Looking back at the case now do you think there's anything you would have done differently?

Yea I think I've learned so if I see a patient like this now I would do the fatigue test and check for reflexes cause that turns out to be a pretty good diagnostic maneuver. It's having to work their muscle and check their reflexes. And you know you don't think of that. You just do a basic neuro exam and check their reflexes but doing it after exercising the limb turns out to be a way of seeing more likelihood if they have it. So I think these specialized neurological maneuvers some of these specialized tests that we don't use a lot to keep in our back of our minds because it's simple and can be done in the office. You don't have to wait a week or two for the antibody to come back.

A: For this patient, after you diagnosed, what decisions did you make at that point?

So at that point yea the ball was already rolling for them to get into neuro clinic. They were they already had the appointment you know then it's clear kind of what you need to do as far as treating it. You suppress the antibody. And actually it's helpful for neuro cause then they sort of have the diagnosis cause otherwise he'd get there and they would be ordering the test and so he's already ready for treatment at that point which is kind of nice.

C: How do you think your rapport with the patient affected your clinical reasoning process, if at all?

Yea I think it helped a lot in the fact that they trust you, they keep coming back to clinic, they report these symptoms to you, they're frank with their answers, I think, to you. They're not trying to hide anything. Also knowing the patient, knowing that they're not a complainer so this is something real you know. I remember as a resident I had to find another area here in -- where you know a lot of -- and so that's its own challenge right cause people have a lot of symptoms. You start to get fatigued it is a fact

that patients will say a lot of these things and you're like is this real or is it just that they're complaining. You know it's a lot of psychological issues whereas I know these guys when they're complaining there's something about that.

C: So I feel like you've given us a great examples of a sort of bread and butter case and one that is more challenging. How do you think your approach differs when you see this kind of cases?

Yea I think you end up going to literature a lot and you bounce ideas off of colleagues. And you wake up at night like oh! I can tell you how many times I've gotten up and looked things up. You write down like information on the patient carry it with you and as you sort of over the day have times to reflect which we don't often do. These are the patients that I think are different because they're the ones that you needed more time to process. I think one thing in internal medicine is we don't have enough time to really process because you're in such a busy clinic that I think if we had cases like this where I can actually make a longer visit, I might be more efficient because I might think about doing that test earlier. But I think what my schedule forces me to do is rule out the bad stuff and kind of think about things later and that's why you have to bring him back the next week after you've thought about it and you've had time to reflect. Whereas I think if I had a longer visit I might be more efficient actually but it's hard to predict.

C: Can you tell us a bit more about your reflection process?

You know you need time and you need a place to do it and I think that it's often at the end of the day after you've finished teaching or finished with clinic. And it's usually you finish your notes and sometimes I do most of my notes and I'll sit there and look up literature and think about all the issues that came up for that patient. It's that quiet time in your office usually at the end of the day. Sometimes I'll do it in the morning too because I'm not that fresh at the end of the day so I'll feel like I actually won't finish my note that day and try to get to the office the next day early. And I find that's really good with a cup of coffee. I'm awake and I can spend the half hour 45 minutes before clinic thinking about the patient the day before so there's a few approaches I've done.

C: And what kind of questions are going through your mind as you're reflecting?

They're really like you know am I missing something here. Is this something that I haven't seen before. Is this something you know that's common that I'm just not thinking about that's just an unusual presentation. The first thing is the unusual presentation of common disease. Now obviously I didn't give you that with this eaton lambert syndrome cause this was an unusual disease. It wasn't that unusual presentation by any means because that's the common way it presents but it's mostly usually a common disease that's just presenting strangely. Like I remember a guy with a pulmonary embolism complaining about abdominal pain. You know so that's a common disease right but that's an unusual presentation so I think that's what I go to first.

C: How do you figure out then whether something is like you mentioned an unusual presentation of common things versus just an unusual…

I think with a common disease it's kind of like the guy I first told you about is really thinking about the key questions of that common disease and really drilling down do they have any of those symptoms or do they have those findings on exam. That's kind of what I did with him. I specifically asked do you really are you sure you're not having pain with urination. Are you going a lot at night. Checking the prostate exam right. So I was really thinking deliberately about questions to ask and things to examine because I

knew that prostatitis is pretty common to an older guy. So I think that's kind the approach with common disease.

C: What helps you decide to kind of narrow it down in that way?

Just knowing what the common diseases are in a patient. And then knowing what those right questions are and what parts of the exam.

C: And how did that process look different for the case that actually was a rare diagnosis.

What was different is I was getting zero bites going down those different paths. Depression, no. Cardiac disease, no. Lung disease, no. Stats are good blood gas is good. The fatigue, the electrolytes. You know I was getting zero kind of clues to go ahead down that route right. And it's like well could this be a rare disease? And yea it was.

C: What do you think a trainee would have struggled with?

That's a good question. With the complicated one?

C: Or either.

Either? Well I think the trainee with the first one the common one I don't think that they would have struggled but it probably would have taken them longer because by experience you know what's more common I think. So I think they probably would have ended up with the same thing but they might have asked more questions in all these different areas and then maybe have a more shotgun approach to the exam and then a more shotgun approach to the workup whereas I think I'm able to hone in a little bit more maybe because I know the questions to ask and you know parts of the exam to do so maybe it's a little more efficient. They might have done more questions done more exams but then end up the same place I think.

C: And how about with the more complicated case?

Yea I think that's a tough one for a trainee because you know what I actually I even see this in internal medicine residents they miss out on these because they don't have the time. They don't have the ability to follow patients longitudinally even in internal medicine. They are on call a lot so they see a patient once and I would say a lot of these cases end up being turfed to the attending even though the residents see them once and has a good diagnostic framework our attendings in clinic that supervise the residents end up often taking over figuring out the last steps. Unfortunately cause the way the training is working now. I think thinking back in the old days when you didn't have the work hours and you had a little more continuity in the res even I the hospital there's a lot of handoffs so the residents have to rely on doing initial workup to rule out the bad stuff I see this all the time. And then they hand off to the next resident the next day that's going to cover. And they're the ones that end up figuring it out. But they get the initial sort of hand off by, so it's a team approach which is kind of nice but the resident that saw them initially doesn't see that case follow through. They end up maybe finding out the result but it was done by a team I think.

C: If we think about clinical reasoning just broadly maybe not with these specific cases but just in general, what do you think students struggle with the most? And maybe we can start with pre-clinical and then kind of move on in training.

I think getting the framework at first. Like I see some students this week. Yea getting a framework for an initial sort of chief complaint and they don't know what's common like I was saying so sometimes they'll throw in things that are really out there and they don't have the common things in there. You know like the abdominal pain, like familial mediterranean fever because it's cool and they write about that and I haven't seen a case of that since residency. It's like on a morning report that somebody else had and it's like well let's think of common things and they don't know what's common. They haven't seen enough. So those two things. Framework and then just kind of pulling out things that causes symptoms but frequency is like one in a million.

C: Do you feel like those two challenges are the same for students across all levels of training or do you think those challenges kind of change over time.

Well they do change because as students evolve and they see more things and they go into wards and then they realize wow I still haven't seen that case of family man.. maybe I should not even mention it. So yea I think experience helps. I think seeing a lot of cases helps. I think that's one of the things that you miss in medical educations. Just exposing the students to multiple cases cause it's drilling and drilling that sort of ends up helping too.

C: How about for residents that you work with?

For residents? So as you go along and I think this is true for early attendings is it's what we call premature closure because they're busy and they're like I've seen this before it's gotta be pain with urination, urinating a lot. Oh it's gotta be a UTI. And they don't even check the prostate. You're like well UTI includes prostate and the treatment is different. Actually 3 weeks of antibiotics vs 1. Treatment is different and they're like so reflexive and busy, and premature closure - I think they get a little cocky. And until they get burned when they get the patient back that says you know you gave me a week of antibiotics and now my pain is back and they're like oh maybe I should have checked the prostate. So I think there's that cavalier sort of mid part of training. I fell for it too. I remember as a 2nd year of resident you know. A few things I felt like was really confident in. You know you've seen all these things now and you can master everything and then something throws you for a loop that's not quite as common.

I think it's interesting you're interviewing people from different specialties I think that might help. There might be a little bit different approach I was thinking of pediatrics or emergency medicine. If you get faculty of different areas I'm just thinking might have a little bit of a different kind of way. I can just see ER it's just more making sure you're not missing anything really severe.

C: Absolutely, especially with the follow up side. I think it looks very different in person to person.

Yea and there's a little bit of that in internal medicine but you know. More reflective and also the fact that you know your patient a little bit so you can use the background of what you know about the patient.

C: I was wondering what you think the role uncertainty plays as you're making these diagnosis?

I think that's where early trainee too and advanced trainee can be different because I think as you get older you get comfortable with uncertainy. I think at least a little more whereas early trainees are really not comfortable with uncertainty. You know maybe the 2nd guy I told you about I was still ok with being uncertain about what was going on and maybe it's a wellness issue because I think when you're

comfortable with that uncertainty you're ok with it because you've had it a few times. You know you're eventually going to figure it out and you got help. Whereas thinking of an early attending when they have that uncertainty they feel like they're a failure maybe. You know they should know it. Why can't I figure it out. It's demoralizing maybe. Because there's a lot of self criticism that people have right in medicine and it's easy to get down on yourself and feel like you should know it. It's a big feel. It's lifelong learning so hopefully as you go along you realize you always have to be humble.

Medicine faculty 3 (internal medicine/hospitalist)

CK: So as you probably know from my email, our goal with this interview is to understand how expert clinicians think through their clinical reasoning process and their clinical decision-making process in general. It might be clinical reasoning or it might be actual actions that you took, but our goal is to really get into the details of how you approach patient cases.

So to start we would love if you could tell us about a particular patient you've seen that you feel like best represents your clinical decision-making process. You can take a few minutes to think about that since I know you obviously see a lot of patients, but if you can think of one particular person and then really take us through every step that you made from the moment the person came into the clinic.

I3: Sure, and by clinical decision-making process you're thinking mostly about diagnostic reasoning, not so much therapeutic reasoning?

CK: So kind of both. It depends on which patient case you choose. If you can think of two separate cases that's fine as well. So if you feel like there's one case that really captures the diagnostic side, and you think there's a different patient case that would better represent the therapeutic side, we're interested in both angles.

I3: Ok, give me a second [laughs].

CK: [smiles] Sure of course. Take your time. You're also welcome to bring in multiple cases if you feel like one case represents one part and then you want to switch cases, that's also fine as well.

I3: Sure. Starting off, when it comes to clinical reasoning, I approach clinical reasoning a little different than most people do. Most people approach clinical reasoning as pattern recognition, saying that if it looks like a duck, and it quacks like a duck, it's probably a duck. I think that's part of the heuristics we use in clinical reasoning in trying to make decisions quickly, which is a necessity in the hospital. And that works for 95% of the time. So like the patient with coronary artery disease who has a history of hypertension, diabetes, and smoking, elderly man, who comes in with shortness of breath that's been progressive with orthopnea, paroxysmal nocturnal dyspnea, and lower extremity edema. You could say ok that pattern fits congestive heart failure. It's almost certainly congestive heart failure exacerbation. And my diagnostic reasoning process – which tests we choose to order, what parts of the physical exam we choose to focus on – are going to be to test that specific diagnostic hypothesis that the patient has heart failure because the pattern so closely fits both the textbook and – actually – it's not just the textbook presentation but also the most common presentation of heart failure. That works quite well for the majority of patients who come in with a variety of symptoms and illnesses.

But there are some patients that doesn't work out so well for. For that I think you need to change up your approach a bit. And this is where I think some people don't like doing this because it takes more time and you have to be much more deliberate, but to take more of a Bayesian reasoning approach where you don't look for pattern recognition. But you ask each question to gather a specific piece of data – whether it's a symptom, duration of a symptom, part of the patient's past medical history, part of the physical exam findings, lab tests – each of these things is a specific piece of data, and some of these things are independent and some of them are not independent. For example, if a patient reports weight gain and they have the physical exam finding of lower extremity edema, those are obviously not independent pieces of data; they're very closely related to each other. Versus the patient who has what looks like pulmonary congestion on chest x-ray and a history of smoking. These two things might not be

truly, truly independent, but they're independent enough that it's a good approximation to say that they're independent. And then to go through the patient case and instead of looking for patterns but looking for these pieces of data that will allow you to refine your differential diagnosis such that you can then ask the next appropriate question.

So for example, a patient comes in with – well the question you asked was looking for an interesting case that illustrates my diagnostic reasoning process. So there's a patient I saw a while ago who presented with new onset liver failure and came in with a recent diagnosis of HIV positivity. This patient presented to an outside hospital with new onset liver failure, not fulminant liver failure, not like he's on death's door. But rapidly progressive. And during their workup, for whatever reason, they took the HIV test, it came back positive, and they diagnosed him with HIV. I don't even remember the diagnosis for what they thought was going on with his liver.

But he came to the [place] for a second opinion. And talking to him, we would say, "Tell us about your clinical history." So we talked a bit about his history of abdominal complaints, onset of jaundice, increase in abdominal swelling, and each piece of data he gives causes you to ever so slightly refine your differential diagnosis. And one of the things that stood out in my mind was the fact that he, when I took the social history, had no HIV risk factors. And it's one of those things that he comes to us telling us he already has a diagnosis of HIV, so obviously your pre-test probability of him having HIV is super high because who's going to make that up, you know you'd hope that no one would ever make that mistake and tell the patient information that was not true.

CK: Yeah, mhm.

I3: But then as you get more data, you have to reevaluate, well maybe something is amiss here, maybe something's just not making sense. Again he had no HIV risk factors – monogamous relationship, no history of IV drug abuse, no substance abuse of any kind, never had any transfusions, didn't have any tattoos. And obviously the patient could have been misrepresenting himself, and a lot of the time when you have a patient who's HIV-positive and claims that they don't have any HIV risk factors, if you're playing the odds, you're going to say that the patient is not being fully honest about something, about whatever their exposure was.

But that combined with some of the clinical features of his liver disease and overall presentation – I remember his fever was a prominent symptom he was experiencing in the context of his liver disease. He had his hepatitis serologies – you know Hepatitis A, B, C, etcetera work – were all negative. That sort of didn't make a whole lot of sense to us. We have to then reevaluate whether some of our assumptions were not right. Our pre-test probability of him coming to us with HIV and whatever the pre-existing liver disease he had – I don't remember what the outside hospital diagnosed him with, maybe it was autoimmune hepatitis or idiopathic hepatitis, something like that – when we have data that doesn't fit with that, we have to reevaluate it. He says that he's HIV-positive, pre-test probability is super high that he's got HIV, but then he's got no HIV risk factors.

And, in my very subjective sense, he seemed like he was being forthcoming and honest. Granted people can fool you, but he seemed like he was being forthcoming. So we had to reevaluate. Maybe something is wrong about the stuff we've been told, maybe some of the information we've been told is leading us astray.

And so, we did a literature search – and I can't remember what the search term was, like literally what the search was, but it was sort of looking for reasons that he might have a false-positive HIV in the

context of liver failure. And it turns out there's actually a whole host of those diseases that cause false-positive HIV tests, and luckily they're all rare.

In his case what stood out was the fact that in his social history he had actually worked on a farm and had a lot of animal exposure – you know goats, rabbits, chickens, horses, the whole bit. And one of the items on the list of things that cause HIV positivity, false positive that is, was Q fever.

And Q fever can present with hepatitis. And so when we saw that, we said alright well this completely changes how we're going to approach this man, because before we were thinking this man has hepatitis of unknown etiology, new onset HIV, no HIV risk factors so that's kind of weird. And looking for the common thread there that linked the hepatitis with what seemed like might have been a false positive HIV test was in this Q fever.

So then the diagnostic decision was, "How do we test Q fever?" And that was just a quick UpToDate search to figure out what's the best assay for that. And it turned out that yeah, he actually had Q fever hepatitis, was his diagnosis.

And after his Q fever serology came back positive, we consulted Infectious Disease to come by and made sure they concurred that when we told him that he did not HIV we were not in the wrong because obviously that would be an equally bad mistake as telling someone that they have HIV when they don't.

CK: Mmhm.

I3: And as far as his diagnosis was Q fever hepatitis, he didn't have HIV at all. And he was placed on treatment, he got better, and presumably he's still doing fine, I hope he's still doing fine. But I guess trying to tie this all into how does this demonstrate my clinical reasoning process, well it's sort of like the combination of not assuming everything you've been told is accurate, it is reassessing the probability of diseases when each new piece of data comes back. In this case, it was the patient has told you he has HIV, but then he has no HIV risk factors, there's no obvious exposure history, so then you have to question whether he actually has HIV. And then referring to literature for things that fall outside your specific knowledge base, like I had no idea what causes false positive HIV tests for that patient, so knowing when it was time to go to the literature. And this process was very long, we probably spent – and by "we" I mean me and the house staff – spent easily 10 times as long, not that you can easily quantify this, but we probably spent at least 10 times as long thinking about his diagnosis than we thought about the average patient.

So you can never be this thorough with every patient, but you know I think another hallmark of clinical reasoning, or sort of a skill of clinical reasoning, is to be able to predict, or to identify, which patient will need much more in depth analysis. You know which patients are the 95% that you can just go with pattern recognition, and which are the 5% that you really have to dive much more deeply into it.

CK: Mmhm. What helps you figure that out with patients?

I3: Ahh, I guess, you know, looking for features that stand out as "don't make sense"? For example – I know you're not participating in this interview so much [laughs]

CK: [laughs]

I3: But I'm going to refer you to [course] for a second.

CK: [smiles] Sure.

I3: In clinical reasoning for [course], we teach about clinical problem lists. And the way I think about problem lists is for a very thorough problem list, every abnormality – you know every part of the medical history, every abnormality, every abnormal test result, every abnormal lab finding, every abnormal physical exam finding, every symptom – it has to be accounted for somewhere in the problem list. Obviously that doesn't mean every symptom gets its own problem list, that would be ridiculous. But every symptom should map to something on the problem list. Every abnormal physical exam finding should map to something on the problem list. Every abnormal test result should map to something on the problem list.

When you look at the patient, when you have a problem list and you have the differential diagnosis – and you have what you can refer to as a working diagnosis, or provisional diagnosis, what you think is the most likely. Then you look to see are there things on the problem list, are there individual symptoms or signs or lab test abnormalities that don't map to something on the problem list, that don't map to the primary diagnosis? So, for example, in a patient who presents with heart failure, let's suppose – oh I'm sorry, I just made a mistake myself. With a syndrome that *looks* like heart failure [smiles]

CK: [smiles] Mmhm.

I3: And you made a note on the physical exam findings – let's suppose you're the world's most awesome physical examiner ever and you actually diagnosed him with something called a Kussmaul's sign. So a Kussmaul's sign, which I won't pimp you on [smiles]

CK: [smiles]

I3: It's an inspiratory drop in the jugular venous pulsations that be indicative of constrictive pericarditis. So let's suppose if someone's clinical syndrome looks like heart failure, and they have you know elevated BNP, they have orthopnea, they have lower extremity edema, they have cardiovascular risk factors, they have echocardiogram showing EF of uhhh – you know other findings of cold extremities, other findings showing that they have poor cardiac output. All these things map onto heart failure, or syndrome of heart failure that you might have on your differential diagnosis and on your problem list.

But then you have this outlier of Kussmaul's sign. And Kussmaul's sign doesn't really map onto conventional heart failure. It wouldn't really map onto any of the patient's other past medical history – they have hypertension or diabetes or hyperlipidemia or what not. It woudn't really map onto any of those. And if the patient, let's suppose he had acute kidney injury or hyperkalemia and all these other metabolic issues that could be related to the primary diagnosis, it doesn't really map onto any of those either. If you were going to draw a concept map, I'm not sure if that's the right term, but up on the board sometimes we do this on the wards, is we just write down all the abnormalities the patient has, particularly for complex patients, and then we draw arrows. What causes what? What's associated with what? And we look to see what's standing out. And if we're trying to draw this map, if we're trying to draw all the connections between all the patient's key features of the presentation, we would find that the Kussmaul's sign is unconnected.

CK: Hmm.

I3: It's not associated with anything else that's up on the board. Maybe that's just random. People can have more than one problem; people can have issues that don't always map into neat diagnoses.

Obviously our understanding of medicine is not complete. Some patients with unconventional heart failure present with Kussmaul's sign, it just happens with some non-negligible frequency. But the fact that it doesn't typically do that would suggest that the patient might need more investigation, that we have to somehow explain why this patient has Kussmaul's sign. Maybe the explanation is we don't know. We thought about it, we looked into other possibilities, and we can't connect it with anything, but we still feel fairly confident with our heart failure diagnosis. But it definitely requires you to think much more, to shift between the pattern recognition and sort of more comprehensive, more in depth analysis when we find a specific sign that doesn't map to anything that you're expecting.

CK: And with the patient case that you described, looking back, what do you think were your most critical decisions that you made?

I3: I think the most critical decision was accepting the patient's word that he had no HIV risk factors. Because that's when we started to think more broadly, that something about this case is not making sense. People don't get HIV out of nowhere. I don't do this with every patient. You know there are definitely other patients I've seen who swear they have no HIV risk factors, and we still work under the assumption that they have HIV. We don't re-test everybody for HIV who don't have HIV risk factors. And why did we make that decision for him in particular to reconsider whether or not that was actually true? You know we tested him for HIV as well, so it wasn't just re-testing because our HIV test was equally positive as was the outside hospital's. It wasn't like the outside hospital's test was a mistake, it wasn't like the assay was misread. It was a limitation of the assay itself. We really had to dive more deeply into the diagnosis. But I think that was probably the key decision was deciding to essentially take his word for it that he didn't have any risk factors.

CK: And what helped you decide to take his word?

I3: [laughs] I don't know. He seemed like an honest guy. [laughs] Obviously there's a lot of bias that plays into that comment. He didn't have any reason to lie, I guess. He came to us for a second opinion, which means he already felt unconvinced that the first opinion was accurate. He wasn't trying to hide his diagnosis; his wife already knew he had been diagnosed with HIV. And she was, as you might imagine, rightfully upset because in her mind she didn't have any HIV risk factors, so obviously that implies that he's doing something that he's not being forthcoming with her about. So he didn't really have any obvious reason to lie about it. And, I don't know, he seemed honest, and it struck us as a strange like – you know new onset HIV presenting with liver failure. It wasn't like new onset HIV presenting with opportunistic pneumonia, that's a very very classic association. Patient comes in with PCP pneumonia with new onset HIV, new diagnosis of HIV, and that makes a lot of sense because that happens very frequently. But patient presenting with new onset HIV – and by new onset I also mean CD4 count was also very low as well, so he would be diagnosed with AIDS at the outside hospital not just HIV.

So being diagnosed with AIDS in the context of acute liver failure, that combination doesn't happen with any significant frequency. There was no opportunistic infection, no remotely common opportunistic infections in AIDS patients that presents with liver failure. So that was also probably a reason why we were questioning whether or not the HIV diagnosis was accurate.

CK: Mmhm. What role did your relationship with the patient play in your clinical decision-making process?

I3: Ahh, well I mean it played enough, again, that we believed him. We had to have some kind of relationship established to have that sense that the patient was being forthcoming. We were also trusting the patient to tell us all the information that was relevant, like going through his social history – you may or may not remember – but Q fever is a zoonotic infection, usually acquired through contact with animals, often on farms. And so, we were sort of relying on him to tell us his full range of all his entire social history; that relied on his trust of us as well. And if you can imagine, this patient just been given essentially – well, I don't want to say it's a terminal diagnosis, but not too long ago it was a terminal diagnosis being told you had AIDS – by another hospital. Well obviously, he's seeking a second opinion, so probably some level of distrust with the healthcare system. Because if he trusted the healthcare system in general, he would have just accepted the first diagnosis and not sought out additional opinions. And so there's already some level of distrust among him, so establishing trust with him to the point that he felt comfortable sharing information was important.

CK: Mmhm. And what other illnesses were on your differential diagnosis?

I3: Well certainly, I mean, I think the key question was whether or not the two things were separate, whether or not he had AIDS and he had hepatitis, or were they overlapping, were they related, or were they totally different diagnoses. So for example, things that would be unrelated was that he just had AIDS, and that was a completely separate diagnosis from his liver failure – and that was sort of visibly the prominent manifestation of his illness because he was jaundiced and had ascites – were things like autoimmune hepatitis, idiopathic hepatitis which is an awful diagnosis, all the hepatitises with the exception of the viral hepatitises because those have a pretty high positive and negative predictive values for the serology, which we had already tested for. So we weren't really considering acute Hep A, or Hepatitis B, because again his serologies were negative for all of those and they're pretty accurate.

If it turned out he was actually HIV positive, if his Q fever never even came up, my guess is that we would have ultimately diagnosed him with idiopathic hepatitis, presenting with acute jaundice and fever and abdominal pain and what not. The other thing to think about is what are some other opportunistic infections that could have linked the two together would be things like, I mean, could you get tuberculosis in the liver? Sure, yeah, you can get tuberculosis in the liver, that's certainly not common. Could you get CMV? Could you get parasites in the liver? There are all kinds of opportunistic infections that could theoretically affect the liver, but they are pretty uncommon.

CK: Mmhm. And so for this patient, how did you decide whether the two problems were linked together or separate?

I3: One thing that pushes you towards thinking they're linked is sort of the younger and healthier the patient is at baseline, the more likely that multiple problems that seem to occur at the same time are actually linked together. So this patient, I think he was in his mid-50s, had no past medical history of note, granted he didn't seem like someone who got a lot of routine primary care so he may have had some relatively minor diagnoses – and by relatively minor I mean things like hypertension and things like that. He may have those diagnosed, but he didn't have any complex medical history coming in, before he got this acute illness. So that sort of leans, makes you think, as a general rule, that multiple problems that crop up are more likely to be related to each other. Versus the 80-year-old who's got status post-MI, COPD, chronic kidney disease, they've had lung cancer that's been treated with chemotherapy and radiation therapy, and now they come in with multiple different problems, you're going to say well maybe they're linked, we should look for a link if there is one, but we shouldn't be surprised if the patient just has multiple things going on with them.

Probably the most extreme example is when you have a healthy adolescent who develops a rash, fever, confusion, and kidney failure. You're not going to be like oh maybe they have 4 different diagnoses? No, like you have an adolescent who was previously healthy, these things are all probably the same problem. And again, for this particular patient, maybe 50 doesn't sound young to you [laughs] but in my patient population 50 is pretty young. And his past medical history suggested that all his problems were probably, probably, linked.

CK: Mmhm. What do you think a trainee would have struggled with, with this case?

I3: I think a trainee would have struggled with accepting that lab tests are imperfect. I see that really commonly where you send off an HIV test, it comes back positive, and you just, alright the patient has HIV, and never going back to the question whether that diagnosis is accurate. We see that – actually I was just talking to someone recently, yesterday in fact and into today, about imaging studies, about histology, and how the fact that we often will treat these results as gospel, as the word from up high. If you send off a biopsy, and it comes back adenocarcinoma, the patient has adenocarcinoma. We just assume that the test is 100% accurate. A lot of people assume that tests don't have great negative predictive value, like we might have sampling error, maybe we biopsied the wrong part of the tumor so that when the biopsy comes back saying that it's a non-diagnostic sample, we think alright it's not diagnostic, it could still be cancer, they just biopsied the wrong spot. And we fail to appreciate that the positive predictive value of these tests, of all tests, is not 100%.

So if the biopsy comes back adenocarcinoma, and it sounds very definitive, we never question whether or not that diagnosis is actually accurate, whether or not it's actually a false positive. We get a CT scan of the abdomen for a patient with right-lower quadrant pain, CT scan comes back acute appendicitis, we don't question alright maybe it's a false positive, maybe the patient doesn't have acute appendicitis. You think that our experience would eventually teach us differently because we take patients to the OR – not we, I'm not a surgeon – but you can imagine surgeons take patients to the OR who have a CT scan that says acute appendicitis, like don't hedge this is acute appendicitis, they operate on these patients and their appendix is totally fine. I don't want to say this happens every day, but it happens within non-negligible frequency, and you think that would sort of teach us that these tests are not perfect, that we should be more cautious before assuming positive predictive values of 100%, but we still don't. We still make these mistakes.

I think a classic example is a VQ scan – ventilation perfusion scan – for diagnosing pulmonary emboli, which thankfully we don't use that much anymore because they're so notoriously – I don't want to say inaccurate – but notoriously misinterpreted, where you can have a patient with supposedly low risk for having a pulmonary embolism, they come in with atypical symptoms, they don't have any risk factors, but there's some reason that the doctor who sees them decides to send off for a VQ scan. And the VQ scans – which you may or may not know – the readings fall into one of four categories: (1) normal meaning it's normal normal, very few patients have a normal normal study; (2) there's low risk, (3) moderate risk, and (4) high risk for pulmonary embolism. And a lot of people make the mistake of assuming low risk, moderate risk, and high risk translates to specific post-test probabilities without considering the pre-test probability. So how this works out in real life is you have a patient who's got a pre-test probability of having a PE let's say of 10%, you know 10% likelihood of having a pulmonary embolism. PE is arguably a "don't miss" diagnosis so to speak, so you don't want to just blow that off. You want to rule it out more definitively, and for whatever reason you get a VQ scan. And the VQ scan is read as high pre-test probability – oh sorry, a high probability scan. And a really common mistake is for someone – not common because it's a VQ scan but because it's a common clinical reasoning mistake – is

to make the assumption that oh it's a higher probability scan so that must mean the patient has a PE, which means we have to anti-coagulate them.

Instead of saying high probability PE doesn't translate to a post-test probability that is the test characteristic, that's not the same as saying post-test probability, so in this case if the pre-test probability was 10% and the patient has a high probability scan, that might make the post-test probability 50%. Yes, that's much higher than 10%, but it's not high enough to say the patient has a pulmonary embolism. You might argue that it's high enough to treat them, maybe it crosses the so-called treatment threshold to put them on anti-coagulation, but I don't think anyone is going to argue that 50% probability of having PE is enough to say that they have a PE, to put that diagnosis definitively on the chart. Yet I would guess that 9 out of 10 doctors, particularly trainees, would do that, would take a low pre-test probability, high risk scan, and put in the chart "Patient has pulmonary embolism." Again because we ascribe too much certainty, to much diagnostic certainty, to tests which are imperfect.

CK: How do trainees learn that that's not true then?

I3: That's a good question. Part of it will be, you would hope that part of it would be experience, like they would see cases that don't work out according to expectations and they would start to question data more. But as I indicated with CT scans and appendicitis, it seems like people don't learn that lesson enough – and I'm not just picking on surgeons. The same thing applies to internists, psychiatrists, and neurologists, and everybody as well.

Part of it is just talking about it. There might not be a whole series of outcomes that seem contrary to expectations, like you operate on 10 completely normal appendices over the course of 10 years. But it could be one specific case that was *so* dramatic that it always sticks in your mind. For example, the patient that I brought up, he comes into us with what looks like liver failure, new diagnosis of AIDS, and we send him out with a diagnosis of Q fever hepatitis that's completely treatable, no HIV whatsoever. That patient is presumably cured and totally fine now. That's a pretty dramatic case, certainly not typical, but the fact it's so dramatic may be enough to have led the house staff who I worked with on that case to think more about the fact that even HIV tests that we think have a really high positive predictive value, that have a really high specificity, even they are not perfect. Do I know that those house staff are going to think twice about diagnostic tests in the future when they have a result that seems not expected? I don't know, but maybe.

I also think that going back to something that I mentioned in the first minute of our talk was looking at cases with more of a Bayesian lens, where you think of every piece of data as having it's own specific test characteristic associated with it. Like a patient comes in with shortness of breath, having a history of diabetes is going to change the probability that the patient's shortness of breath is caused by heart failure. Whether or not the patient has an elevated JVP is going to change the probability of whether that patient has heart failure. But with a diagnostic test, that's no different. So if you're very deliberate about the clinical reasoning process, if you think about it from a Bayesian standpoint, you are always going to look at every piece of data – that includes diagnostic tests – as having test characteristics. So instead of saying oh this patient's BNP is elevated, well a lot of people make the mistake of saying elevated BNP equals heart failure, which is not true. And if you approach the case from a Bayesian standpoint and say alright, how does an elevated BNP affect the probability of a patient, who has shortness of breath, how does it affect the probability that it's caused by heart failure. We're not going to accept it as the diagnostic test, or as the gold standard for example. And if you force yourself to look up the positive and negative predictive values are for BNP as part of the Bayesian reasoning process,

then it will force you to acknowledge the fact that these tests are not perfect. It's sort of built into that whole style of clinical reasoning.

CK: So you mentioned at the beginning of the interview that your approach of using this Bayesian model is sort of unusual. How did you end up adopting this approach?

I3: Reading about other people who did it, to be honest. Reading books about clinical reasoning. There's also another hospitalist at the [place] who is a real fan of Bayesian reasoning, and we've talked about it some as well. I'm sure we've probably to some extent reinforced each other's view that this is the preferred model for, particularly for, challenging cases, again rather than pattern recognition which is much more common and easier.

Just to highlight this fact – I can't remember what year you did [course] in, but for two years in a row I did a lecture on something called the "Threshold Model of Clinical Reasoning" where you think about probabilities and whether or not they've crossed certain thresholds of diagnosis. For example, probability of a disease in a patient crosses the "rule out" threshold, as in the probability is below the "rule in" threshold, then you say alright well the patient does not have this diagnosis, so we won't work it up anymore. It's more involved than that, but – so I gave this lecture for two years and at the end of the quarter, as you know, students give feedback on the different classes and courses. And you know, you typically don't get feedback on individual lectures, but once in a while you do. And that was by far the least well received of any lecture I've given in the medical school [laughs]. And it was interesting because it was a good example of how you can never really judge how successful your teaching is until you talk to the learners. Because some things that you think seem really clear and obvious and make a lot of sense often times your learners just don't get or are not picking up. And vice versa, some things that you think are very convoluted and you think you did a terrible job, sometimes your learners really thought that was effective.

But it turns out that this Bayesian analysis that ties in with the threshold model of clinical decision-making, it's not obvious, it's not natural. You both have to have a lot of deliberate thought about it and enough clinical experience that you have some context to which you can apply the model. And students and other trainees – interns, residents – they (a) honestly don't have the time to sit down and read some textbook about it like an attending might 10 years out. And (b) they might not have enough clinical context to really appreciate how to apply the model successfully. And so when I've tried teaching it, it ended up being a train wreck. It didn't feel like a train wreck to me, but apparently it was a train wreck when you read the comments about it [laughs]. So I don't teach it anymore. I would love to be able to teach that later on down the road, and I know – speaking of [person], the other hospitalist at [place], they teach some of this material to interns and residents who maybe have more experience and have heard of some of the terminology a bit more. It's just not as natural of a way to think about things. Pattern recognition, heuristics, rules of thumb, is a much more natural – they're much easier to grasp, which I guess is good because they work most of the time. If you tried to apply Bayesian reasoning to every case that worked in the door, you'd be the world's most inefficient doctor and you'd probably be thrown out of the hospital on your butt.

So on one hand it's good that rules of thumb are effective most of the time, but again some cases – we teach clinical reasoning and focus on it a lot in POM not to diagnose the 95% of cases that are easy. Because to be honest, if you had no clinical reasoning taught in medical school and you just learned all the pathophysiology, you learned the physical exam, you learn how to interview patients, and you just imagine that the clinical reasoning thread did not exist, you would probably do ok on about 95% of

cases, that are straightforward. It's really only 5% of the cases that are not straightforward that the clinical reasoning thread is really aiming to help people to diagnose.

CK: Can you tell us about another patient case that maybe represents more of the 95%?

I3: Sure. We had a guy, a patient who presented at [place] a few weeks ago, who had a history of lymphedema that was predominantly in – it was asymmetric – I think it was his right leg. He had lymphedema, idiopathic, going back about 10 years, 10 or 15 prior episodes of cellulitis related to his lymphedema, since lymphedema impairs your circulation and predisposes you to getting cellulitis in extremities affected by it. And, like I said, he had 10 or 15 prior episodes of cellulitis. Who presented to the ER with his leg being red, hot, and painful, and his chief complaint when he walked through the front doors and talked to the triage nurse, I think his chief complaint was, "I have cellulitis." [smiles] So that's a patient where you hear the story and you're like well, if they've had it before, they probably know whether this cellulitis again. I went down to the ER to see him, and he had an asymmetric edema of his right leg and it was red, hot, swollen, and tender. His white count was a little bit elevated, and otherwise his labs looked fine. He looked fine otherwise from mid-thigh down – I'm sorry, I mean mid-thigh up he looked otherwise fine.

And so it was cellulitis. It wasn't a diagnostic mystery. The pattern matched an illness script, so to speak, very very well. There were no features of his presentation in his past history, no exam features, no lab tests that were inconsistent with the diagnosis. So we were talking about how every abnormality has to map to something on the problem list. In this patient's case, every abnormality mapped to cellulitis, and so that was a patient where pattern recognition was sufficient. We didn't feel like we needed to do anymore investigation, we didn't need to think harder about that patient. It was very straightforward.

CK: Mmhm. And how do you think your reasoning really differed from this patient who's sort of more the common case versus the previous patient that you described, which was more of that 5%?

I3: Not to sound too simplistic about it, but it's more like you have to make a cognitive switch where you say this patient, there's something different about this patient, I need to think harder about him or her. Sort of the Type I versus the Type II thinking, which I don't know if you're familiar with, you know the fast subconscious thought process, which is like pattern recognition, versus the slower more deliberate thought process, which is more like the Bayesian reasoning of like let's break open the textbook and let's look at the literature. And whether or not those two processes truly map to two different parts of your brain [laughs] like some people will talk about.

But I definitely feel like when you're seeing patients you have to make that switch. You have to say something about this patient is not making sense, so I'm going to flip this switch, I'm now going to be in the more deliberate mode versus I'm going to be in the pattern recognition mode.

CK: Mmhm. And what tips you off to know to make that switch?

I3: I think it's largely it's whether or not there are features that don't fit the pattern. Does this pattern fit an illness script? And if it doesn't fit any illness script perfectly, why does it not fit perfectly? Also keeping in mind that illness scripts are themselves imperfect, and they're imperfect because our knowledge of disease – individual knowledge of disease is imperfect. Our global knowledge, the medical profession's understanding of certain diseases is imperfect, so illness scripts are never 100% accurate. The less consistent the presentation is with an illness script the more likely it is we're going to have to make that cognitive switch to be more deliberate about the thought process. If the patient's

presentation fits an illness script 100%, and there's no deviation, and you could imagine like taking the patient's presentation and like creating a [course] case for a clinical reasoning session out of that patient's case, well that's probably not a patient we don't need to be that deliberate about. And not because patients aren't important, but just because we can't take the time to be deliberate with every patient. It's just not practical.

CK: What role do you think basic biology mechanisms play in your clinical decision-making process?

I3: It helps me understand I think why – like for example, if we were to think about a case more Bayesian like, so thinking about a patient with heart failure. I keep going back to heart failure, but we'll stick with that example. And I'm trying to understand whether or not a patient case in front of me is heart failure or not. I think having a knowledge of the basic biology helps me to predict, to better estimate and/or better remember what the test characteristics are of not just tests but also exam findings and what not. So for example, like BNP. Like some people just think BNP equals heart failure. But if you know that BNP, you know B-type natriuretic peptide, is actually secreted by myocytes in the right and left atrium in response to atrial stretch. You don't necessarily directly apply that knowledge to patients, but I sort of do in the sense that that will make me realize that oh well there are other things that cause stretch atrial myocytes rather than just heart failure. So for example pulmonary emboli can do that. Constrictive pericarditis can do that. There are other diseases that can do that. And so that will lead me to consider other diagnoses and will lead me to be able to better predict sort of how sensitive or specific that specific test is. I can't remember the vast majority, like 99% of test characteristics, I don't remember those numbers. There are a tiny, tiny small handful that come up all the time that I do, but most of them I have no idea. And so I have to have some way to estimate them, and the best way to do that is usually a little bit of experience but also to understand the basic biology behind it.

CK: How do you decide when you have enough information to move forward?

I3: Do you mean to move forward with a treatment plan, or move forward with a diagnostic test to confirm?

CK: Either.

I3: Going back to the threshold model for a second – that probably confused you if I happened to have taught it to you, I apologize [laughs]. We have what's call a "rule in" threshold and a "treatment" threshold, and those are not the same threshold. So for example, the "treatment" threshold is when you have a probability of a disease that crosses above the "treatment" threshold, let's suppose it's 70% or 80% or 90%, when it's above that threshold, then we say alright when we think about the risks and benefits of treatment, we're going to go ahead and treat this patient. It doesn't necessarily mean that they have the disease, but the risks and benefits of treating them if they have the disease favor treatment at this point. And then there's also what we call the "rule in" threshold, which is the threshold 70, 80, or 90% whatever, of the probability of the disease, where if the probability crosses that threshold we conclude that the patient has that diagnosis. And we say that diagnosis has been ruled in. Those thresholds aren't the same, and what sets those thresholds, there are a lot of different factors that go into that. There are these things like how dangerous is the disease, how dangerous is it to miss the disease, what is the likelihood of alternative explanations, is there an easy diagnostic test that will confirm or refute our diagnosis. Like for example if you feel really confident that the patient has strep throat, but there's the rapid strep test, which is super easy and super cheap to get in the clinic and you get the answer back within minutes. Like even if you feel really confident that the patient has strep

throat based on their history, you might go ahead and get the rapid strep test. Let's suppose you think the patient's risk for having strep is 90%, that's pretty high. And you say, alright 90% is pretty high but I'm not going to rule it in because it's really easy to be absolutely sure with a rapid strep test, and so we're going to go ahead and get the strep test and try to push that 90% probability to 95 or 98%, like for the probability that they have strep throat.

Versus another disease, let's suppose you think someone's got neurosarcoid. And you're 90% confident – that would be weird to be 90% confident that someone has neurosarcoid, but let's just suppose you're 90% confident that someone's got neurosarcoid. And you're thinking alright how do I push that 90% higher, can I do that? And let's suppose you've already done the MRI scans, you've done the serum ACE levels, you've done examinations for other manifestations of sarcoid throughout their body – you've looked at the joints and their eyes, you've looked at their heart – and the only diagnostic test is a brain biopsy to push that diagnosis of neurosarcoid above 90%. Brain biopsy is much more invasive, no one's going to do that for neurosarcoid, so you might say 90% for neurosarcoid that's as good as we're going to get. There's no test that's going to push it higher, so we're going to go ahead and say that this patient's got neurosarcoid even a probability of 90% is the same probability of a patient having strep throat that we thought was not sufficiently high enough to make the diagnosis.

Other deciding factors might be like public health risk. Like for example, for a patient with tuberculosis, or suspected tuberculosis, the fact that the patient is going to be at risk not just for themselves but also for spreading it to everyone else in the community, other healthcare providers, and their families. That's something that's going to affect at what levels, at what thresholds, are we going to decide that someone has either ruled in or ruled out the diagnosis of tuberculosis, or HIV, or lots of other communicable diseases. Some diagnoses carry specific connotations or some sort of specific baggage associated with them. So for example, syphilis. If you're diagnosing someone with syphilis, irrespective of the danger it actually poses to the individual and irrespective of the public health danger, syphilis has a connotation associated with it that carries a lot more baggage than someone being diagnosed with HPV. Is that fair that syphilis has a worse connotation than HPV? No, probably not fair [laughs]. But it does. Because of the additional emotional burden that it has on the patient, that might change how sure you want to be before you tell someone they actually have syphilis versus telling someone they have HPV. Even though you could make an argument that HPV might actually be even the more dangerous diagnosis, just because the average patient doesn't have the knowledge what that actually does.

CK: Mmhm. What role does uncertainty play in your thought process?

I3: A lot. So yeah, uncertainty is a big problem in clinical reasoning, both uncertainty and being comfortable in that uncertainty, and having your patients be comfortable in that uncertainty. And it goes back, again, to talking about these thresholds, these rule in and rule out thresholds, when you tell somebody, you know you have colon cancer. And the patient says, how sure are you that I have colon cancer, are you sure? You told me you have colon cancer, but does that mean there's no chance that I don't have colon cancer? That means you're 100% sure? Well, no. As I was saying earlier, not even biopsy samples are 100% accurate, pathology can be wrong, histology can be wrong. And probably colon cancer is not the best example because actually it has pretty good positive predictive value for diagnosing that, but something like COPD is maybe something that is – telling someone they have COPD or emphysema is a diagnosis that has a little bit more diagnostic uncertainty associated with it. If you think about it being very objective, it's just based on PFTs, but PFTs are not perfect for a variety of reasons. So you can imagine a patient, and both of this patient's parents died from emphysema, they have a lot of emotional investment in whether or not they have that diagnosis. And so they come in with

chronic shortness of breath, you're worried about COPD, you get some pulmonary function tests, and the combination of the symptoms, the exam, and the pulmonary function tests suggest that it's consistent with COPD. It's consistent with the patient having emphysema for example. Does that mean the patient definitely has emphysema? No. But how do you explain that to the patient who's so, again, invested in the diagnosis that like you know I'd say you have 95% chance you have COPD. It's enough certainty that I would put it on your chart. It's enough certainty that I'm going to prescribe you treatment for it. It's well beyond the certainty that I'm going to tell you to quit smoking. But is it absolutely certain? Well no, it's not absolutely certain. There are very few diagnoses where we're absolutely certain. And having the doctor be comfortable with uncertainty is one issue, and having the patient be comfortable is the other. I think the obvious thought would be that patients have more trouble with uncertainty than doctors do, but I think doctors have a lot of problems with uncertainty also. I think a lot of doctors don't want to feel like they don't know the answer.

This comes up on things like discharge summaries. Maybe it feels a bit non sequitur, but with discharge summaries, a patient comes into the hospital with a new set of symptoms or signs, and you do a diagnostic workup, maybe it's one of the 95% of cases where it's obvious or maybe one of the 5% cases that are not obvious. But if it's one of the 5% cases that's not obvious, you have to be more deliberate with the thought process, and sometimes you figure out the answer and sometimes you don't. It's really unusual to find a discharge summary that someone says I don't know. Like discharge diagnosis acute liver failure unknown etiology, or sepsis unknown etiology, or non-cardiac non-ischemic chest pain unknown etiology. People don't like putting those diagnoses down on discharge summaries, and maybe it's because they don't code very well. You know for billing and coding, they have to attach an ICD-9 code or ICD-10 code to everything, maybe some of those uncertain diagnoses, some of those uncertain terminologies, don't map very well to ICD-10 codes. But it's obvious that people don't want to feel like they don't know. There's a lot of resistance to saying – so if a patient comes in with chest pain, super common presentation to the hospital, atypical chest pain. And you rule them out for having ischemia, in other words you don't think they're having angina from ischemia, from coronary artery disease. But you don't know what's causing their chest pain. It's super common to find doctors, everyone from interns to attendings, writing down all kinds of garbage on the discharge summaries saying oh, costochondritis, esophageal spasm, GERD, musculoskeletal strain, etcetera. They don't mean those diagnoses. I mean diagnosing esophageal spasm, that's a super invasive, very rarely made diagnosis with any degree of certainty. Like no one is actually going to do that. Like put down these pressure manometers down to your lower esophageal sphincter to actually measure – no one actually takes those steps. So instead they just put the word down on the discharge summary because they feel like the discharge summary has to have a diagnosis because they feel like the patient has to have a diagnosis.

Another related thing to discharge summaries is death certificates. I've been in some arguments with coroners where a patient of mine has died, and the family has declined an autopsy. And I get the call from the coroner asking for the cause of death to put down on the death certificate. And I say, I don't know. Patient had lung cancer, they were here for chemotherapy, and they had a PEA arrest out of nowhere, and they died. And I don't know, it could be a massive PE, it could be a massive MI, it could be a pericardial tamponade, I don't know the family declined an autopsy. And the coroner will say, no you can't say I don't know, you have to give a diagnosis, you legally have to give – this is not by the lawyers, but I've been told this by the coroners – that you have to put an actual medical diagnosis down on the death certificate. And I say, I'm sorry I just can't do that. I can't just make up – I can give you my best guess, but I'm not going to say that this is what caused it, I'm going to say this is a possibility. At least in [county], you can't do that. You can't have suspected MI, suspected saddle embolism, suspected VTach

arrest. It has to be a diagnosis. It's almost as if the coroner doesn't appreciate the fact that there's uncertainty in diagnosis.

So uncertainty is a big problem. And that we always feel like there has to be an answer even when there's not always an answer.

CK: Mmhm. How do trainees handle uncertainty compared with attendings, or people who have more experience?

I3: I think everybody struggles with it. I don't think it's something that attendings struggle with less than trainees do. I think attendings will acknowledge it more, I think they will say like uncertainty is a problem. And they will acknowledge the fact that there's a lot of cases that are idiopathic where we don't actually know. But I don't know if they struggle with it less just because they acknowledge it more. I think everyone feels some degree of unease with not being able to give patients diagnoses. There are certainly some diagnoses that I feel like – the exception would be a diagnosis that frequently has no explanation like going back to chest pain. Like I would say the average patient who comes into the hospital with atypical chest pain leaves without a diagnosis. They may have a diagnosis on the discharge summary, it may say "costochondritis" or some completely BS diagnosis there, but I think most of those patients don't have any actual diagnoses made. And because it's so common I feel like that diagnosis I feel comfortable – I mean I would have no problems whatsoever writing down my attending note for that patient saying, non-cardiac, non-ischemic chest pain I don't know what the etiology is but I feel comfortable saying it's not anything imminently life-threatening. That's just because that specific presentation is something that I've seen so many times and other hospitalists have seen so many times.

Versus the patient that comes in – this is a hypothetical patient that comes in with unexplained 30 pounds of weight loss. Poor appetite, 30 pounds of weight loss. You do what you think is a reasonable workup for that patient, and you can't find any explanation. They don't have any malignancy you can identify, they're not depressed, they don't have hyperthyroidism, they don't have any of these sort of classic things that can cause weight loss. And that feels way less – that feels way more unsettling to me because that's a presentation that's way less common. And it feels like we're missing something. Like the patient that comes in with atypical chest pain, we rule out coronary artery disease, I don't worry about that patient when they go home. Like I want them to get follow-up, and I want to make sure they see their primary care doctor to see how they're doing, but I don't get concerned about that patient dropping dead from undiagnosed coronary disease when they walk out the door. But the patient with 30 pounds of weight loss without an explanation, that patient I definitely worry about when they leave. That's the patient that I will check up on the chart every couple of weeks just to see if they came back to the hospital, if the diagnosis was actually made at some point, and to figure out what the diagnosis was. Was it something that we missed? Was it something – you know was the patient diagnosed with some weird autoimmune disease, or was diagnosed with having military tuberculosis or something? Was there some feature that we missed when they initially presented that, something to learn for next time? That type of uncertainty I don't think attendings do better with than interns. If anything an intern might feel even less worried about the uncertainty because they're so busy that they've already moved onto the 150 other patients that they don't have time to think about the patient they just discharged 2 weeks ago.

CK: How about the role of reflection? Can you speak a little about how that fits in with your thought process?

I3: Some of it is what I was just talking. Some of it is going back to – is following the patients you felt uncertain about, that you didn't have a diagnosis or you made a diagnosis but you didn't feel it was as rock-solid as you wanted it to be. I think it's a form of reflection to go back to the chart after a couple of weeks and sort of follow up and see what happened with the patient. I think talking about cases with other people is sort of a form of reflection. Something that we do at the [place] hospital – I know [place] isn't unique in this and that other hospitals do it as well – but is to have a multidisciplinary conference where every week on Wednesday at noon there's a conference where a challenging case is presented. And sometimes it's a "fresh catch" case where it's a case that doesn't have a diagnosis and people are presenting it with the hopes that – the whole department attends this, everyone from the medical students all the way up to the chief of the department. Sometimes it's a "fresh catch" where the people presenting actually want other people's input to figure out what the diagnosis is. But more often than not, it's a case that is in the past. It's a case that had a challenging diagnosis to make, a diagnosis that was missed, a bad outcome where the diagnosis was made but where the patient still had a terrible outcome but because of a systems problem or what not. And that gives a chance for reflection because as a member of the hospitalist group, I'm tasked with presenting one or two of those per year, and then often times even for the ones we don't present, other people who are presenting will ask us for suggestions for cases to present in that conference. So they'll say oh hey, I'm presenting the multidisciplinary conference in 3 weeks, do you have any cases you think would be cool to discuss? And you know if there was a case that was challenging, or a case that was on my mind, or something that I wasn't sure about, something I want to hear other people's opinions about, then maybe I'll suggest that case. When it's presented, there's a panel of different specialists that talk about the case. For example, there'll be one person at the lectern, going through slide by slide – here's the past medical history, here's the HPI, here's the physical exam. And then there's 3 or 4 specialists – there might be a hospitalist, a pulmonologist, a surgeon, a psychiatrist, a social worker, etcetera – and they'll talk about the case. And sometimes if it's your case it's helpful to be on the panel, but it's actually more helpful to not be on the panel. So if someone says oh hey I have this case coming up, do you have any interesting patients I can present? And I give them a patient, and then I don't actually be on the panel and I just be in the audience and listen to other people's insight on the case. I think that's uh – it's not directly reflection but it sort of helps with it because you hear other people's thoughts on it, and then it helps you sort of reconsider your own approach to the case to see whether or not you were on or off about it.

CK: Mmhm. I'm just going to check the time so I can make sure. Oh it looks like we're out of time. And I want to make sure since I know we have a one hour block with you. But I think we covered everything. Let me just look through.

I3: Ok, I hope that degree of rambling was ok.

CK: That was perfect, yeah [smiles]. Yeah, I think we covered everything. Let me go ahead and pause this.

Medical faculty 4 (oncology)

CK: okay thank you so much for being with us here so today as you probably know what we're trying to do is get a sense for what does it mean to be an expert in clinical reasoning and so we are defining clinical reasoning sort or broadly - so also the diagnostic process but also the diagnostic process as well. And so to start us off we would love to hear about a case that you feel best exemplifies your clinical reasoning process. and we would love to hear about it in as much detail as you can think of and so does step-by-step the decisions you made with the patient from the moment they came into the clinic and it feel free to take a minute to think.

E: Ok. So this is a little bit of a funny question for me because as a medical oncologist pretty much everyone I take care of in the hospital and literally everyone who is referred to my clinic comes with the major diagnosis already being made. In fact it's true that it is a prerequisite to come to my clinic that you have a tissue diagnosis of cancer. If you don't, you can't get into my clinic. So of course we still make smaller diagnosis, but I think it will be more helpful for this discussion if I go back to when I used to attend on the General Internal Medicine wards because those are where we really make a diagnosis, where we go from having a very puzzling situation to making a diagnosis.

So let me let me actually take a case that is one that I participated actually towards the end but I'm quite familiar with the entire process that led up to the diagnosis. And I think it's a case that illustrates a lot of very good diagnostic principles.

So there was a gentleman - this was probably 4 years ago or so - who had received most of his care at another regional hospital not at [place]. And basically what happened is that he had been otherwise healthy and had started developing fever. And so he had presented to the other hospital with these unremitting fevers. And they did the same thing as we would have done. They presumed that he had an infection they did kind of the preliminary, almost rote, workup for an infection. And basically they did not find any evidence of a specific infection but still they assumed that he had an infection of some kind and placed him on a certain relatively broad spectrum antibiotic. He had some improvement and so they sent him home. Then a couple weeks later, he came back to the hospital again and said that the fevers had gotten better for a little while kind of on the antibiotics but then really persisted pretty much the whole time and then more recently before the readmission had grown even worse. And so they had admitted him again And this time they did what I would call the sort of million-dollar infectious workup. So you learn if you're an internist on the inpatient wards for very long that 90% of people who present with a fever will have pneumonia, urinary tract infection, diarrheal infection, may be a CSF infection meningitis - between those four diagnosis you'll capture almost everybody. then if you look for those things and none of them reveals the diagnosis and you still don't know what's going on, then there's kind of a next-level workup, which involves - so there's actually like an algorithm in medicine called fever of unknown origin that involves sending off a bunch of pretty obscure labs for things like babesiosis and Q fever and culture negative endocarditis and anyway there are a whole bunch of other things. So they did that whole workup. Also unrevealing really didn't know what was going on, but he seemed to be sort of stable enough to discharge so they discharged him. So this process repeated it itself three or four times at the regional hospital and then finally on about the fifth time he came to [place]. By the time he came to [place] for some number of months now he had been having these unrelenting fevers. In addition to the unrelenting fevers he had now had a million dollar workup which had really been completely unrevealing, but then he had also started to develop other problems. So at first he developed general fatigue, then the worsening general fatigue progressed into actual paralysis - so first he completely lost the use of his legs and then developed this sort of ascending paralysis where he also

lost the use of his arms. In the face of this, he also began to lose weight very significantly and over the course of many weeks lost probably 40 or 50 pounds, and then in the face of this, he continued to have these unrelenting fevers. And so by the time he got to [place] you know his presentation was significantly more complicated than it had been at the beginning and his condition continued to worsen. And he had now gotten not only a million-dollar infectious disease workup, but also a million-dollar rheumatology work up and a million-dollar neurologic workup. And all of it was completely unrevealing. So then finally when he was admitted to [place] they noted that in addition to all of his many other problems, he also began to develop significant anemia and thrombocytopenia. Now that's a complicated thing in a patient who is as sick as he was because oftentimes in patients who have sepsis - which in spite of the negative workup at least some strong element of sepsis continued to be a possible explanation for a lot of what was going on although probably not for everything - but in any case with serious sepsis you can develop significant cytopenias just from that but because everything else was going on because they didn't have a good explanation for what was happening yet they performed a bone marrow biopsy. The bone marrow biopsy - we have wonderful Pathologists, and the pathologists were able to look in the walls of the blood vessels that were biopsied when they took a piece of the bone marrow. And in and around the walls of the blood vessels they saw hiding this exceptionally rare thing called intravascular lymphoma. So they diagnosed him with lymphoma.

And then he was referred to oncology and when he was referred to oncology he started a very standard lymphoma regimen called R-CHOP. And over the course of which he got 6 cycles and then over the course of six months it was like watching Lazarus in slow motion. He regained the use of his arms and then regained the use of his legs and then started walking again, the fevers resolved. He regained the weight, his blood counts went back to normal. And the last I knew of him which was a couple of years ago now, but the last I knew he was getting close to being back to where he had been before he was sick.

CK: So looking back on this case what do you think were the critical decisions that were made?

E: I mean I guess there are sort of two ways to answer that question. I mean in a sense the critical decision that was made - the thing that finally uncovered this very elusive diagnosis - was doing a bone marrow biopsy. You can make an argument that that was kind of the key that finally unlocked the door to figuring out the diagnosis. But at the same time there were - in a case like that where the diagnosis is very difficult to come by much of what you have to do is rule out all of the much much much more common things before you arrive at a point where you rule in the thing that's really going on.

To be honest I don't remember precisely when he first started developing the cytopenias although I think it was actually relatively late in his course. I don't think it was there before. You could ask an interesting question, which is should have gotten a bone marrow biopsy before? But you know it's really very very very rare to find the answer to an elusive fever on a bone marrow biopsy. So you know I think that for the most part he received the care that he should have. It just turned out to be a very difficult diagnosis.

CK: Can you speak a little bit about what the rule out process looks like?

E: Yeah so when you're deciding what to rule out, what I usually teach my students is that it's actually a pretty complicated calculus in one sense. So on the one hand, you can kind of think of a set of scales. So on one side of the scales, you have a - you could think of it as a product. And that product is the

likelihood of a diagnosis multiplied by the seriousness of the implications of that diagnosis for the patient or in rare cases for other people around them if it's an infectious illness or whatever.

So that's on this side of the scales. And then on this side of the scales, you have the cost of doing the procedure that would lead to the diagnosis. Right, so if it's for instance an MRI that costs $10,000 that's very different than if it's a chest x-ray that costs $20 or whatever, plus the risk to the patient for doing whatever the work-up is, plus - I don't know - the expense in time or in other words I guess you could just consider the cost broadly. And so I think you have to weigh those two things against each other. And when the when these things, out way these things, then you should probably do the test to try to rule the diagnosis out. Now it actually is then even more complicated than that because the other thing that you have to factor into the diagnosis - into that calculation is the characteristics of the test.

So in other words if you - let's say that you have a diagnosis that is not particularly likely but would have grave implications for the patient if it were there. But then you would have to consider the characteristics of the tests that you have to look at the diagnosis. So if the test characteristics are such that you that you lack either a sensitive test or a specific test - or maybe you have one test that is sensitive but not specific, another one that is specific but not sensitive - you may have to in that case do two tests, or you may have to do a test with the understanding that the test in and of itself is not going to be sufficient to rule out the diagnosis if you don't have one that sufficiently sensitive. And so all of that has to be taken into account when you then - and of course the tests have to be interpreted in the context of your pretest probability which is related to your clinical judgment. And so it really is actually quite complex both deciding what things you need to rule out and then deciding what you need to do to sufficiently rule out the things that you feel you need to rule out.

CK: And so with the patient case that you described before, what sort of diagnoses were being ruled out?

E: Oh all kinds of things. You can think about - it's kind of like digging a well in the sense that you start with the things in the first layer of dirt that you dig out so to speak are the very common things. So first you rule out as I said before pneumonia, urinary tract infection, meningitis, diarrheal illness those sort of things. Then on the next level down you start ruling out things like babesiosis, endocarditis, Q fever, etcetera. Then on the next level down you start ruling up things like occult cancer, rheumatologic diseases like rheumatoid arthritis, neurologic diseases like multiple sclerosis. This case was made more complicated because as your descending down these layers, you're dealing now not just with a fever but also with all of the other things that attend to that.

And then eventually you get all the way down to trying to rule out things like what he actually had, which you know you can probably see a hundred thousand patients with a fever and never see a patient who has the fever because of intravascular lymphoma. It's a vanishingly rare entity. But if you have ruled out all of those other things in the levels above and that's still there then at some point you get to having to look at things like that.

CK: And how are these layers structured, in that it seems like there is some pattern for how they go down?

E: Yeah well I mean, if I were thinking of mapping this, I think the way that I would map it is [pause] You could think about it as a spectrum, where you have 0 at the bottom and 1 at the top. And then you could give a numerical score to - and the numerical score would be from 0 to 1 as well. And so the score would be derived from two numbers. So you would, first you would rate the probability of the given diagnosis

from 0% to 100%. And then you would rate on a scale from 0 to 1 - which I'm sort of making up - the gravity of the diagnosis also from 0 to 1. And then you would multiply those things such that if you had for instance a diagnosis that was a 0.9 in terms of gravity and a 0.9 in terms of likelihood, then that would get you an overall score of 0.81 which is quite high. And so that would put it higher on the list of things that need to be ruled out. Whereas if you had something that had a 1% probability, even if it were going to be quite grave that would score much lower and could probably be ruled out later. Having said that, while I think that's a reasonable general framework within which to think about how we do that, I will say that in practice that's not always true. In the sense that sometimes there are things whose implications are so grave that even if the likelihood of the diagnosis is particularly weak we still rule them out routinely and very early because you just sort of can't miss them.

And so I guess in some sense, I think that my idea of a sort of likelihood-gravity product holds as a general organizing principle, but with the caveat that we have sort of arbitrarily set some threshold that if the gravity is above say a 0.9 - obviously these numbers are sort of silly - but if the gravity is above some certain threshold that we've set, then if there is any realistic probability at all, no matter how small, we just rule it out anyway.

CK: And so for you in practice what does that threshold look like?

E: It's a good question. I think it would be very difficult to definitively and precisely articulate, which frankly may be as much as anything be a criticism of the fact that we haven't been as careful about this as we should be. As you are aware having been in these classes with me, when we teach clinical reasoning as a class to our students we teach it in a way that is - we talk about can't miss diagnosis. And we kind of have a list. So if you come in with chest pain, or you come in with a headache, or you come in with back pain, or whatever, we have for each of those - we have a list that we sort of come up with that you just can't miss. The idea of can't miss, the idea of that whole category of terms, is that if there's a person who presents with XYZ complaint, you just have to make sure that their diagnosis is not ABC. But of course the problem with that framework is that if taken to its extreme it leads to a very sort of - well it leads to a mindset where medicine becomes about, depending on your point of view, if you're noble it becomes about preventing terrible outcomes but at the expense of essentially being paranoid. Or if you're more cynical, it comes at the cost of trying to prevent a lawsuit all the time right.

Because then you could say, well okay so for a headache a can't miss diagnosis is a subdural hematoma or a subarachnoid hemorrhage. Well that's true, certainly if they have a subarachnoid hemorrhage you would want to know about it. But does that mean that every single person who comes into your clinic with a headache should get a CT scan? No, it probably doesn't. By the same token you could say well for low back pain a can't miss diagnosis is cord compression from metastases from an undiagnosed tumor. Now you know it is true that if someone has that and you leave it undiagnosed or untreated, they can develop lifelong paralysis. So but while it's true that that's a can't miss diagnosis, it's also true that the vast majority of people with low back pain don't have that. And if you did an MRI, which is the appropriate test if you're concerned about that, for every patient who came in with that complaint that would be a poor practice of medicine.

And so I think I actually that if you look at medical culture, there is a sort of a tug and pull between those two forces - sort of the idea of a can't miss diagnosis and the idea of prudent usage of our medical resources. And I fear sometimes - it's interesting because we teach this idea of a can't miss diagnosis in medical school, but I fear sometimes that the idea has gone too far in the sense that now, as one example, there is something called the Choosing Wisely campaign. I think it was sponsored by the

American Board of Internal Medicine. They basically went around to a bunch of their subspecialty groups and said - this is not how they phrased the question but one way you could, what they basically said was, “What do you think are the 10 tests that are ordered too much in your sub-discipline, and how can you advise people about how they shouldn't be ordering those tests all the time?” So one example of that is ordering MRIs for low back pain. But another way of phrasing that question is, “What do you think are the 10 places where people are abusing the concept of a can't miss diagnosis and using that as a sort of surrogate for clinical reasoning, or as a sort of cop out for thinking hard about cases so that it's just that every person who comes in with x complaint, we're just going to do this thing because it's a can't miss, when probably something like the product that I described earlier - not that that's you know the exact right formula - is something like that would be more appropriate.

CK: Given that you're a medical oncologist, as I mentioned in the beginning we're really interested in also hearing about therapeutic decision-making. And I was wondering if maybe you could talk about a case where you feel like there's a patient who best exemplifies what you feel like therapeutic decision-making looks like, maybe someone you’ve seen recently that way we can go through the steps of how you thought through that?

E: So that’s where as a medical oncologist in a funny way we don't do that much leg work in terms of diagnosis, but in terms of therapy decisions I feel like that's where I spend the bulk above of my - well one half of the bulk of my emotional energy. And also most of my mental energy is in making therapy decisions, so I'll give you a good example.

It's quite complex in a sense so stay with me. So whenever - so I'm a medical oncologist, which means that I give chemotherapy to people with cancer. So I don't do surgery and I don't do radiation, but I work very closely with radiation oncologists and surgical oncologists. So the two cases where I get involved in people's care are one if they have incurable disease and let's set that aside for a moment and not talk about that. But the other is when we are getting ready to give either neoadjuvant or adjuvant chemotherapy. So what that means is we have learned over time - there have been many many many many trials that have demonstrated that for many kinds of cancer you will have a better chance of beating the cancer forever if you have a surgery to take the cancer out and then get chemotherapy and sometimes radiation either before or after the surgery, than if you just get surgery by itself - with the idea being that although the surgeon will take all of the cancer that he or she can see when he or she does the surgery, there will be some cancer cells in many cases that the surgeon just can't get. So if we give chemotherapy and radiation we can eliminate the rest of the cells from the body. But as you can imagine this poses all kinds of really thorny at difficult problems for doctors.

The biggest thing is that the stuff we’re doing make the cancer cells not come back is by definition toxic. And sometimes it's really toxic. And so you know that's kind of yucky. If you're a doctor you went into medicine to help people and now I'm administering poison to them all the time. I mean that is really quite true. Chemotherapy is basically carefully controlled poison. So first of all is just that it sort of seems backwards to be doing that on the one hand. The second thing along those lines is that there are so many questions about chemotherapy that we don't really know the answer to. Fo instance since we - so we decide that for a given cancer we think it might be helpful to give chemotherapy afterwards to get rid of those rogue cells. So how do we answer that question? We do a clinical trial. How do we design a clinical trial? We give somebody - we take people who have had a surgery let’s say for colon cancer - take 200 of them, randomly divide them into groups of a hundred apiece, and then give one group chemotherapy and one group not. And see who does better. But for the group who gets chemotherapy, there's a whole bunch of questions like what dose of chemotherapy, how long should they get it for, all

those kinds of things. And what we largely - what we do in those cases is we just choose arbitrarily. We pick a dose based on preclinical studies and then we pick the length of time frankly based on just what we've always done. There's no good reason for it.

So in colon cancer until a couple of years ago everybody who had colon cancer that had spread to their lymph nodes got 6 months of chemotherapy after their surgery. And there is very good evidence that that would help instead of about 50 out of a hundred people beating their cancer that would be 70 out of a hundred people beating their cancer, so really significant improvement. Then a couple of years ago there was a trial presented in our yearly national meeting where they asked the question what if - so it turns out that 6 months of chemotherapy is quite toxic. And in particular it leaves about 10% of people with lifelong nerve damage that is at least a nuisance, sometimes truly painful, and sometimes debilitating. So then the question was asked, what if instead of giving 6 months of chemotherapy what if we gave 3 months of chemotherapy instead thereby avoiding some of that long-term neurotoxicity - could we still have the same effectiveness of the treatment? So they did this enormous study with like ten thousand patients - it was actually a conglomeration of like six more studies but anyway - it looked at like ten thousand patients. And what they saw at the end of this was - so they had to do a study called the non-inferiority study, which has very strict criteria where basically you have to prove beyond a reasonable shadow of a doubt that therapy B is as effective as therapy A and basically what it showed was that while giving 3 months of chemotherapy was really really really really close to being as effective as getting 6 months, it didn't quite meet those stringent criteria. So strictly speaking it was a negative study. So we had a patient who came in and he a lot of - one thing I should say is that there was one very small group within that study. Basically if they had what's called a T3 tumor, which is to say a tumor that invaded relatively deeply but not as deep as some do because there are T4s - if they were T3 and N1, meaning that it had spread to not very many lymph nodes, those patients it looks like they do okay with 3 months instead of 6 months. So I saw a patient about a month ago who came in with a T3N1 tumor, so it was the kind of tumor that fit in that small category of people who seem to do just as well with 3 months as with 6 months. But he also had what were basically two clumps of cancer cells that were next to some of the lymph nodes but not actually inside of the lymph nodes. And we know from other studies that if you have those little clumps of cancer cells that are distinct from the main cancer that that portends a worse prognosis. So he came in and as you can imagine as most people, he would really prefer to get 3 months of chemotherapy instead of 6 months, but only if it was going to be as good as getting 6 months. And so the question was should we give him 3 or should we give him 6? And attempting to answer that question based on available data is really really hard because strictly speaking - so first of all strictly speaking you could just say look this big study was negative and it failed to meet its endpoint, it did not show that 3 months was as good as 6 months, end of story, he should get 6 months.

Then you can say, well yes but there was this post-hoc subset analysis that showed that if you were T3N1, which he was, the 3 months was as good as 6 months so he should get 3 months. But then you could turn around and say, well but a post-hoc subset analysis is not statistically valid. Any statistician will tell you that it's a negative study, so he should get 6 months. And furthermore he should get 6 months because even though he's technically T3N1, he has these little clumps of cancer cells that have been shown to portend a worse prognosis so if anything he needs it even more than if you were T3N2, so there's no question that he should be getting therapy, as 6 months of therapy. And the truth is that at the end of all of that back and forth we don't know the right answer. And as I said hanging in the balance is not just his likelihood to beat his cancer and have it never come back, but there is also the likelihood even if he never got more chemotherapy there's still like a 50/50 chance that he would go on to live a normal healthy life free from cancer. And assuming that he does that, we have good data to suggest that if you give 6 months of chemotherapy rather than 3 months that you have a significantly, really

significantly higher risk of having lifelong neuropathy. And so trying to make the decision between 3 months and 6 months is very challenging.

CK: So how did you end up making that decision?

E: Well so I guess I would say two things. One is that within reason I have a sort of conservative viewpoint on these questions, though whether conservative is even the right adjective in that instance is debatable. But basically what I mean by that is as long as I'm not unalterably harming the patient, if there is a thing that I can do now that will significantly reduce the risk that the cancer will come back in the future my inclination is to do the thing now even if - so long as I have reasonable evidence that it will be helpful. Having said that, I also recognize that all decisions about medical care ultimately should be made by the patient. And so I view my role not as making the decision but as explaining the evidence, making a recommendation when appropriate, and then asking the patient to make a decision. So in this instance, I explained to him a sort of shorter and less medically jargony version of what I explained to you a minute ago, and then said, based on all of this stuff that we just discussed my recommendation would be to get 6 months of chemotherapy, but having said that ultimately the choice is up to you.

CK: And what was the ultimate decision?

E: The ultimate decision was - we kind of hedged. So we're going to aim for - he's still getting his chemotherapy now - we are going to aim for 6 months. But having said that - so the chemotherapy consists of two drugs. One of the drugs, generally if you tolerate it well at the beginning you'll tolerate it the same way all throughout, not too big of a problem. The other drug is the one that causes the long-term neurotoxicity. So basically what we've decided is that we will for sure do the first drug for 6 months. We will try to do the other drug for 6 months but will have a relatively lower threshold for taking the second drug out if he starts to develop any significant degree of neurotoxicity.

CK: And what kind of symptoms would you be looking for?

E: So people generally at first develop cold sensitivity. Then often times at first that symptom will last maybe even just while they're getting chemo, or like the day after they get chemo. Then it will start to last a few days, and then maybe even a week, and then eventually you can start to last all the way through until the next cycle. Then in addition to that, they'll develop at first very subtle and then more pronounce numbness and tingling in their fingers. And then after that they can start to develop some difficulty with fine motor movements in their fingers with things like buttoning buttons and counting change and that kind of stuff. And then if we continue to push dosage, then they develope the more severe and often long-lasting neuropathy where they just can't do - it feels like they're wearing like gloves or mittens all the time. You just can't do things like button buttons. So we ask about those things every time they come in. But I can - if they're starting to accumulate some degree of the neurotoxicity then we'll generally reduce the risk or stop the drug entirely. But having said that, it's also true that sometimes there is a delayed worsening of the neuropathy.

So I had another patient recently who we gave him 3 months of chemotherapy before his surgery - it was a different kind of cancer so you get part of it before - anyway we gave him 3 months and then - so you have like a month after the end of your chemo to rest before your surgery and then you have a month or so after surgery to rest again. Over the course of those 2 months, even though he got no chemotherapy over those 2 months and even though he had no neuropathy of the beginning of the 2 months, about the time of the surgery he started to develop neuropathy. And then it started to worsen as he went through the rest of his therapy such that by the time he came back to restart his

chemotherapy after the surgery, it was continually getting worse even though he hadn't seen the drug in 2 months so in his case we gave him 3 months of both drugs and then 3 months of just the one drug on the back end.

CK: So you mentioned before that the patient is very involved in these decisions. What does it look like for your relationship with the patient in terms of how that affects certain decisions that you make? I know you mentioned it before but maybe a bit more detail?

E: So this is another one where I think you can go to, I think there are inappropriate extremes of the answer to this question on both sides. So on one side and you can have a person who would say do - well so the old-school model of medicine was paternalistic. You go to the doctor and often times my understanding is that the doctor wouldn't even fully explain to you what was going on. The doctor would basically just say do this, or stop that, or have this surgery, or whatever. And it was just the presumption that the doctor was the one with the training, and he knew what was best, and that's why you were going to him - was to have him or her fix you - well often it was him in that case. Then over the last 10 or 20 years, I think that the pendulum has swung really far away from that, to the point that now I think that some - especially medical trainees but even some doctors - feel like it's not even their place to make a recommendation because it should be such a patient-centric model that patients should just get to decide everything and make all the decisions. I think that probably the right answer is in between there. I think that what is, I think the difficulty in, the reason that we've ended up with both of those extremes - both of which I think are falsely premised and ultimately incorrect - is because we failed to differentiate between the fact that on the one hand, there are goals and priorities, and on the other hand medical facts.

Most patients don't have a deep understanding of medical facts. That's why they're not doctors. But what they do have is a deep understanding of their values and priorities. And so my understanding is that we should use our expertise to convey to the patients the pertinent medical facts, and then help them to understand how they can use those pertinent medical facts in combination with their values and priorities to make a decision that will best benefit them. So in some cases there's almost nothing to talk about because you know - if the thing is, if you have gangrenous cholecystitis and you are septic and you need emergency surgery, what is there to discuss right? You either have the surgery or you die, and I mean unless someone is actively suicidal - which even if they were that's a separate discussion - there's sort of no version of values that says I would rather die, assuming it's a young healthy person and whatever. But on the other hand if it's this super complicated thing like what I was talking about a minute ago, where it's you know, well would you rather have an 8% greater likelihood of lifelong neuropathy for a you know 2% greater reduction in the lifetime risk that your cancer comes back? That's a really hard discussion. And so - but I think that our job is to try to boil it down to its essence, and then present it in a way that the patient can use their values and priorities to then make a decision.

CK: And so with the patient case you described before about the cancer patient, what role did your relationship with him play in that decision making process?

E: That's a good question. The truth is that at the time we made that decision, we didn't really have much of a relationship yet because I had just met him. I think the time that my relationship with patients comes much more directly into play is when I'm helping my patients make decisions about their care as they near the end of their lives because that I think is a totally different, a totally different story. Because in that case, often times these are patients who I have known for months if not years. And in

that case I think that the trust that we have built up over all of that time allows us to communicate in a way that is vulnerable and honest enough I hope to facilitate me helping them to make that decision.

CK: And is there a specific patient case that you can think of that exemplifies that process?

E: [details redacted for privacy]

CK: Looking back on this case what do you think was the critical decision that you made?

E: I think the critical decision that I made was to recommend that she go home on hospice rather than try and receive more chemotherapy. Now for whatever it's worth it was not a decision that I made like lightly. And it was one that I questioned multiple times and went back and re-litigated with myself multiple times, including calling at least two of my mentors to talk through the case with them and explain my reasoning to them to make sure that they felt that the way I had reasoned through that decision was sound. And even after having done that with them twice, two different people rather - there were still questions around the time that I made the decision I still questioned whether I had made the right decision. It really wasn't until I saw how things unfolded over the next month that by the time she died I was quite confident I had made the right decision.

CK: And what's going through your head when you made that recommendation?

E: Well the reasoning that was going against my making the recommendation is that I think most oncologists are at heart optimists. And I wanted to believe that the next treatment would work even when the last one two three four five or so drugs have done nothing. You always want to believe that oh well maybe this one will be super effective, or maybe if we can get her on this and then just keep her on it for a while, then she can you know there'll be some new trial that opens here and she can get on the trial or maybe this or maybe that. You always want to hope for that. That's one piece. And the other piece that made it hard is that there's always a sense of - no matter what you do there's always a sense of guilt. There's always a sense of oh should I have you know picked up on some sign of the tumor's biology changing earlier, or should I have sequenced her therapy differently, or should I have pushed for this procedure, or whatever.

Anyway, all those things were going against. But at the end of the day I just, I mean that one frankly was, for lack of a better word, my clinical Spider Sense and my clinical interpretation of the CT scan. I just when I, as I said I can still remember very distinctly the way the CT scan looked. When I opened it just was clear from the CT scan and then to a lesser degree from the lab values and how she was feeling, even if we pushed for maximally aggressive and invasive therapy, I was pretty confident that it was not going to do anything productive. Now you know the irony as with all clinical decisions is that you never really know if you made the right one. I mean you can kind of know in the sense that I have a very strong sense - but I did for the reasons that I described. But can I absolutely prove that if we had given her this other chemotherapy that it wouldn't have had a dramatic effect? Very unlikely but I can't prove it, it's possible. [details redacted for privacy]

CK: You brought up the tumor's biology and sequencing. I was wondering if you could speak about the role that understanding biological mechanisms, or the basic science, how that affects your clinical decision-making?

E: That's a good question. You know there are - it's relatively rare, I'm trying to think of counterexample to this, but I think it's fair to say that it's relatively rare that a particular biological fact leads in a "A leads

to B" kind of way to making a particular clinical decision. But what is true I would say is that - well two things. There are cases of that, but I can't think of any cases of a time when I like knew some you know biochemistry factoid that I had in the back of my brain from 20 years ago and it saved the patient or something like that. I can't think of a time like that. I can think of two sort of related things. So one is - as you probably already know - is that it's very common in oncology now to get We get genetic sequencing on like virtually all our patients. And the idea is that if you sequence the tumor and look for the mutations that it might have, then you can take treatment X because treatment X does a good job with mutation A. I will tell you that in most of my practice, we see people all the time where ninety-plus percent of them get nothing from it. It doesn't change our therapy - well either it changes it in ways that we already know about like there are certain - for example in breast cancer you test for something called HER2 expression, which is a kind of genetic test. And it's very well-known in breast cancer that if they are HER2 overexpressing than their treatment is totally different. So for that kind of situation, there are times when we know about specific genetic questions. But for just doing like the whole genetic - like the whole exome sequencing or whatever - it's unusual for that to play a role outside of the roles that we already know about.

But there are a couple of patients that are like that. I had this one patient - probably the worst cancer that I take care of is pancreas cancer. It's very aggressive. It's very difficult to treat, almost everybody who has it does very poorly from it almost from the get-go. And yet what - I have two patients, one of whom had failed all of the standard treatments for pancreatic cancer. And not just failed them, but had failed them like boom-boom-boom. Like he had gotten this therapy, it worked together. He got this therapy, it never worked. He got this other therapy, it never worked. None of them ever worked. He had run right through everything. He was from [place], and he was this close - like literally days away from traveling back to [place] to be with his family to die. And then we had seen that he had gotten a result of one of these tests that he had this one particular mutation. And so we referred him to a doctor who had a trial for a therapy that was directed at that mutation. And we got him on that therapy. He's had zero side effects from it. He started it like a year ago, and the tumor hasn't grown a millimeter since then.

And then we have another patient who had pancreas cancer. It grew slowly through his first treatment but still grew after like 6 months - who also had pancreas cancer actually but who had a totally different mutation. But we got him onto a different therapy. And he's been on it for like 10 months and then the tumor shrank, and it hasn't grown since. Rare, but occasionally it does. The more important thing - that's sort of a niche case. The more important thing is that all of the stuff that you learn in medical school - it's rare as I said that some factoid is like the key that unlocks the door. But what is not rare is that all of that stuff you know - I made a point of taking my notes in medical school in these beautiful bound notebooks. And I still have the beautiful bound notebooks. And occasionally I am - there are like this many of them if you put them up next to each other. And I still look through them, and I don't even know all of this stuff that's in them anymore. But if you learn all of the - here I am telling this to the educational PhD who probably learned all of this and memorized it, this probably sounds ridiculous and simplistic [laughs]. But anyway, here's the way I think about it is if I learn all of this stuff, all of these facts, now 10 years after medical school, I might only remember in a like explicit way - that I can really articulate only this much of it. But all of the other stuff forms this kind of a, like a scaffolding. It's not that I remember the things, but it's that learning them - even if I later forget them - creates this sort of a neural network that is then the - it's like the derivative of the stuff that I learned. It's like the stuff beneath the stuff I learned is the stuff that equips me to be able to think about really complicated, nuanced, difficult cases in a way that hopefully allows me to like connect the dots and try to understand things holistically in a way that I think is is meaningful. And you know I think that to some degree that some of the difference between - so I have a couple of friends right now who are getting degrees to

become physician assistants. And it's really interesting because physician assistants here at [place] - with a couple of exceptions - basically just do the first two years of the MD curriculum. So all of that stuff that I memorized, not quite all of it but most of it they learn it just like I did. But I think that the difference is that then when you go on into in my case Internal Medicine residency and then Oncology Fellowship is that you're then taking all of that stuff and sort of using those raw materials over and over and over again to fashion these sort of longer-lasting expansive neural networks. Anyway that's how I think about it.

CK: I wanted to ask you a couple last questions. So what role does uncertainty play in your clinical decision-making process?

E: That's - it's the defining characteristic of being a doctor. And it's the thing that keeps me up at night. You know when - so I'm a very, I'm a pretty aggressively and self-consciously self analytical doctor. So this happens in the clinic too but it's all put into a sort of fast forward when I'm on the inpatient service because everything is happening so quickly on the inpatient service. When I attend on the Inpatient service, almost every day and then especially after I finish a two-week block, I go home and try to think to myself is there anything that didn't go the way that I wish it would have gone today and is there anything that I could have done differently to make it turn out the way that I wish that it would have turned out. And all of that centers ultimately around uncertainty because you're - most of the time when you make medical decisions you are making decisions in the face of uncertainty, even when it - because at the beginning you don't know the diagnosis. But even when you do know the diagnosis, just like I was discussing with that one guy with deciding whether to get 3 or 6 months of chemotherapy, there's just no certainty. There is no right answer. And while it's true that sometimes we see patients where there is a right answer, there are a lot of instances where there is no right answer. In fact, the majority of instances, there is no right answer. And so you know that's definitely been one of the things for a young attending that has really - that really weighs on me and as I said keeps me up at night is that you know you want, you always want to do the right thing. And usually the right thing is at least clearer, if not totally clear, in hindsight. But since you can't live life forward with hindsight, you have to operate in the face of uncertainty and then live afterwards with the consequences and sometimes that's hard.

CK: And what role does reflection play?

E: Yeah I well as I said - so there was, there's a guy at [place] who's an internist. I think he's still there, he was there at least a couple years ago. There was this guy named [name] and he is a hospitalist there. But he also used to give a talk to the residents, probably still does, he talked about how if you - so you know how internship is described as feeling like drinking from a fire hose, which is totally fair. But if you - the reason that it feels like that is because you're on this very steep part of your learning curve. And what he talked about is that if you look over a person's training, intern year is like this. And then our two year starts to plateau, and then our three year starts to plateau even more, which paradoxically the shallower the slope of your learning curve the more comfortable you feel. The problem is you go from this, to this, to this and then many people almost as soon as they get to be attendings, level off almost entirely. And then many of them pretty soon start to go back down. And so the challenge becomes - and this is the thing that he talks about in his talk - is how do you keep that learning curve with at least a positive slope and hopefully a significantly positive slope you know perpetually. And I think that there are sort of two main elements to that. One element is a continual reassessment of the literature. Right so you have to be keeping current with the newest advances. And then the second thing is a process of self-reflection. So I always tell my students that the most dangerous thing in medicine are the things that you don't know that you don't know. The things that you know that you don't know are fine

because you can just look them up. But the things that you don't know you don't know is where you really get hurt. And so in some ways I think that the most important element of self-reflection is that it allows us to recognize and then hopefully learn to cover our previous blind spots. So if we have an unintended outcome, a bad outcome when I'm on service, then I feel like part of our responsibility as a team is to work backwards and say how did we end up here? Now sometimes bad things just happen. We take care of patients with advanced cancer, and sometimes they're sick and sometimes bad things happen and that's just the way it is. A sometimes bad things happened because we didn't do as good of a job as we should have of anticipating this possible problem, or because we missed a telltale sign of something, or because our clinical reasoning wasn't as sound as it should have been and we weighed something too much and we should have weighed something you know more or whatever. And I think that reflection is the process that allows us to identify those things so that we can then keep that slope positive and fine tune things to be just that much better in the next encounter then we were in the prior.

CK: Given the timing, I think we'll end here.

Medical faculty 5 (OB-GYN/surgery)

CK: Thank you so much for being willing to be interviewed for this as you might know already from the email the goal of this interview is for us to really get a sense of how you as an expert think through your clinical decision-making process. So this might be the actual clinical reasoning to get to a diagnosis, but it could also be how you decide to get specific test results or how you decided to move forward with a treatment plan.

E: Ok

CK: So we would like you at this point to try and think of a specific patient case that you feel like best represents your clinical decision-making process. And then feel free to take a few minutes to think about that patient case, and then once you have a sense of which case you want to talk about if you could take us through all the different steps that you took from the moment the patient came into the clinic.

E: Ok. I think the case I would choose is one that is in some ways a composite but it's a situation that is really pretty frequent related to adolescent gynecology. And it's a clinical situation with acute onset of pain, and the patient typically a teen who comes into the emergency department typically with acute onset of unilateral pain. Do you want me to just tell you more about the case?

CK: Yes, that would be great, and if there's a specific person that you can think of.

E: Ok [pause]. They just all run together in terms of being just very very similar, and I think I think about them all in a similar similar kind of way. So usually I am getting the history second hand from my residents who see the patients in the emergency department, although it's not rare for me to be called by a community usually pediatrician with the story about the patient and you know, what do I do, what should we be concerned about overall? With my residents, I have asked them to give me some certain information about the patient as an identifying piece of data - identifying pieces of data - because in order to think logically about the patient I need the information. So I teach residents and students on the GYN rotation to give me the patient's age, their gravidity and parity - have they had a pregnancy in the past, have they had a delivery in the past. The date of onset of their last menstrual period because the clinical situation needs to be interpreted in the context of the menstrual cycle. Whether or not the patient acknowledges being sexually active because certain causes of pain are much more likely or much less likely if they're not sexually active for example. Whether or not they're using any current method of contraception and their concern, or their complaint, chief complaint basically. So that is for me the identifying sentence with no details further about it. And that let's me start to think then about the details for the patient.

Probably, well they're - all of those pieces of information are important. One of the most important pieces is if she is menarchal, that is has started her periods. Where she is in her menstrual cycle because the causes of pain - and usually we're talking about lower abdominal pain slash pelvic pain. And we are interpreting that as I say in the context of the menstrual cycle and the causes of pain which might be an ovarian cyst, the types of cysts vary by where she is in the cycle and - or if for example she's also on oral contraceptives then we don't expect her to be forming a functional cyst, a follicular cyst or corpus luteum cyst because she shouldn't be ovulating if she's on oral contraceptives. The causes of acute gynecologic pain are typically torsion or rupture of an ovarian cyst, less commonly just the presence of a cyst. Usually the cyst needs to do something or have something happen to it for it to be painful.

And then of course there are other causes of acute pelvic pain, especially if it's right sided we think appendicitis. But I do have one patient right now in my practice who has situs inversus and came in with an ovarian cyst and it was confusing until she and her mom told us she has situs inversus. So at any rate, we're interpreting in that context. So the menstrual cycle important. The onset of the pain and the characteristics of the pain are important, so I'm thinking about a torsion or a cyst rupture usually pretty acute onset of pain. One can also have bleeding into a cyst that is acutely painful as well. So again cycle dependent. If the pain is a little more gradual in onset, if they're been associated symptoms like fever especially if she's sexually active, then we start to think of things like pelvic infection and pelvic inflammatory disease (PID), pelvic abscess, PID - particularly if she's not used any protection or is not using barrier condoms, which she might be using in addition to a hormone method of contraception.

We of course always think about ectopic pregnancy and any pregnancy-related issue as well, so the sexual activity figures into it. And of course one of the things that we would do in terms of labs ultimately is always an HCG or pregnancy test, even if she is not able to acknowledge to us that she is sexually active. We may not have asked the question the right way, she may not trust us, there are a variety of reasons that she might not feel comfortable acknowledging sexual activity and missing a pregnancy-related acute problem is just so important that it's not that we disbelieve her, it's that we really have to have objective evidence to that effect. So we would always get a pregnancy test with abdominal pain in a female of reproductive age. I was really gratified - I just got the feedback from this year's [course]. And in the comments, one of the comments was the lesson is always get a pregnancy test. And I was thrilled [laughs], so I said yes, that is a take-home point! At any rate, we do always get a pregnancy test.

So I jumped ahead to labs and I don't think I want to do that yet because they're many other elements of the history that are important as well. I've mentioned the onset of the pain, the characteristics of the pain, if it were more a colicky type of pain we might - I mean there are other causes, things like pyelonephritis or a stone that can kind of present with lower quadrant pain as well. Urinary symptoms UTI, always in the differential. So you wanna get and hear about urinary symptoms, we want to hear about GI symptoms as well. Of the GI symptoms one of the most important in thinking about torsion, which is a really hard diagnosis to make and which is really based on our clinical assessment more than anything else, it's helped out by radiology but it's really our clinical assessment. And most of the studies with torsion suggest a pretty strong association with nausea and vomiting with the acute onset of really severe pain. So all of the characteristics of pain that we teach - the patient's description of pain, the severity of the pain, the exacerbating and alleviating factors. All of those kinds of things are important in my practice with adolescents, is to calibrate them for their assessment of pain.

Most adolescents have not had a whole lot of terribly painful kinds of events. I sometimes joke they haven't been through labor as have women who have had a pregnancy. And so women who've ever had a pregnancy or a labor calibrate everything else in the context of labor. And so a 10 out of 10 pain for someone who's been through labor is quite different honestly than a 10 out of 10 pain for an adolescent who's just never experienced that. I would still take her seriously if she tells me that the pain is 10 out of 10, but I do want to calibrate. And the other thing that's really helpful there is the mom's assessment, or the parent's assessment of the kid's pain tolerance basically. When I'm in the clinic I can ask that privately. If I'm in the emergency department, I usually I need to ask it in front of mom, but sometimes moms will volunteer. They'll say, she never complains of pain, this is really unusual that she's having this severe pain now. Or usually she's pretty much of a wimp. And some moms will say that in front of daughters, which is a little bit sad but at any rate they - and sometimes they will joke about it and make light. But that kind of calibration of the pain is really helpful for a teen, or younger child in particular.

So that related to the pain. I mentioned the things that are on our differential, so I'm considering the differential as I go along and I get the history so I mention symptoms of a UTI. I will note symptoms related to pregnancy as well, and especially teens don't always put all these symptoms together. But as an OBGYN, the classic symptoms of early pregnancy a - which can be nausea and vomiting not just related to the acute pain but more at other times. Urinary frequency as the uterus enlarges and presses on the bladder. Fatigue, which sounds like a really soft symptom but for who women who have ever experienced it in early pregnancy, it can be pretty profound and notable. And amenorrhea of course. So those are really symptoms of pregnancy that we would kind of want to go through one, two, three, four, five kind of thing. So bowel function I've mentioned, but the nausea and vomiting particularly pointing if it's associated with acute pain, pointing potentially to a cyst rupture or a cyst torsion as well. It probably the pathophysiology may relate to some tugging on the peritoneum, not entirely clear but very clear that torsion in particular is associated with nausea and vomiting.

The patient's underlying past medical history, really important as a context. Most of the teens that I see with an acute episode of pain are pretty healthy people, they don't have underlying medical problems. But if they've had, if the patient has had previous surgery - I see a lot of patients who actually have very complex past medical histories as well. But patients who may have had a kidney transplant, or may have had even multiple congenital anomalies, surgical repairs. And those patients who have had intra-abdominal are more likely to have adhesions and scarring that make the likelihood of a torsion less likely. So if they've got adhesions, and everything is stuck to everything, the ovary is less likely to twist than if they've never had intra-abdominal surgery. So that past history of surgery is really important. So we think about that, we think about other underlying medical problems, so those kinds of things are important.

I mentioned contraception, I mentioned sexual activity, those things that would lead more toward pregnancy possible as - of course a ruptured ectopic pregnancy. Other symptoms we would actually ask about, but the patient may volunteer include peritoneal signs. So they may tell me that as they were coming - if they came to the ED by car, they may tell me that the car went over a bump and it really hurt, or it hurt to walk. So the classic symptoms that would suggest peritoneal signs that I'm going to find on exam are important. And then with intra-abdominal fluid like a ruptured ectopic and bleeding, or ruptured cyst and bleeding, symptoms like diaphragmatic irritation. And even syncope as a symptom with acute intra-peritoneal blood loss. So if we see a patient who has a positive pregnancy test, it's an early pregnancy, thus a pregnancy of unknown location, we may - if we really don't think she's got a ruptured ectopic right now, but we can't prove is it an intrauterine pregnancy or an ectopic pregnancy, we would give her what we call ectopic precautions, which are in this day and age I think a little bit outdated - we say if you faint or if you have right upper quadrant pain or hiccups, anything that would suggest diaphragmatic irritation, then come back in or call us and come back in. But that's waiting for it to rupture and that - we really now most of the time make the diagnosis before an acutely ruptured ectopic pregnancy. But certainly if she told us she'd had a syncopal episode that would be really important in her history overall.

I'm trying to think if there's anything else that I would ordinarily think about related to past medical history. Not so much that's pertinent to the acute onset of pain that I'm thinking about right now. I mean we always want to know the usual sorts of things like allergies, and medications, and if there are any meds they're taking currently as well. One question that we should always ask is, have they had an episode like this before? Similar pain? What were they told about the diagnosis at that time? One of the things that we are finding with torsion is that in our patients who here at [place]. But when we looked at our patients who had a surgically confirmed torsion, 40% of those patients had more than one twist in

the adnexa. So with an episode of torsion, when the ovary twists, typically with an acute - one twist is plenty enough to cause acute pain. So when we see more than one twist, we think is this something that is more - and the term hasn't been used and we are submitting a paper where we will describe this and hope the term will be used in the future - but a chronic torsion that has happened once in the past. They had an acute episode, the torsion didn't completely occlude blood supply, so the ovary is still viable. But whatever caused it to twist in the first place, and often it's twisting around a cyst, the cyst is still there so that it twists again and has not just a 360 twist but a 720 twist. And in our series of patients we weren't able to, because it was a retrospective chart review, we weren't always able to determine whether the patient had had a previous similar episode of pain. But given that 40% of our patients had more than one twist, it's one of the things we should be asking more often is have they had a similar episode previously. So we've got our our history of present illness, we've got our past medical history, we're thinking about what labs we're ordering, and often the ED has sort of ordered their usual before we are called, which virtually always includes an HCG pregnancy test and a CBC at the very least, and often a basic metabolic panel as well. So we would have those things, and often we would want to see a transabdominal pelvic ultrasound or possibly a transvaginal ultrasound if they are sexually active. So we would, when we talked to the ED probably have ordered those things, so those things are usually pending by the time we see the patient.

So then moving on to the exam. And with the exam, as always, what does she look like? Does she look like she's sick, does she look like she's in acute pain, is she doubled up in pain right now. Or is she looking as if she's pretty comfortable. So we will observe her, we will look at her vital signs, is she tachy, is she hypotensive, all of those things that are important. Is she febrile. So looking at vital signs. We listen to heart and lungs, but as gynecologists, we're not usually called to assess those kinds of problems [laughs]. So yeah, and we'll check for CVA tenderness because of pyelo or a stone or something - urinary tract is on our differential. The abdominal exam, we will listen for bowel sounds. If they are absent, suggests ileus that can be associated with a ruptured ectopic or intra-abdominal bleed as well. The other thing that's on our differential but pretty rare in a teen and especially when one who's never had surgery before is a bowel obstruction. So in that case we would hear high pitch bowel sounds, so in a patient who'd had significant bowel surgery in the past that would be one of the things on our differential - is a bowel obstruction. So the quality of the bowel sounds is important. And then we would ask about any particular tenderness, have her point to where the area that's most tender. And we would do as we teach, our light palpation and then often a fairly surreptitious check for rebound and peritoneal signs.

Sometimes patients are hard to calibrate and everything is hurting and they're just really uncomfortable, so a little hard to distinguish does it hurt more when I push or when I released the pressure and palpation. We usually would try that first, but if it's a little equivocal and she's not sure, then we may sometimes even as we are listening with our stethoscope use the stethoscope to apply pressure and then lift up on the stethoscope and see if that maneuver, which they are not appreciating as a palpation in quite the same way, whether that causes them to grimace or causes pain. We're watching their face as well as listening to what they say as well. So all of those things are important. We might or might not not do a gynecological exam. If she'd been sexually active in the past, particularly if we were worried about infection, we would do a speculum exam. We'd look for a purulent discharge. We'd look for the presence of any bleeding in the vaginal vault. We would do a bimanual examination, assessing first of all how they tolerate the pelvic exam. So if they've never - we'd ask before doing it if they'd ever had the exam before, and we'd explain it as we would go through the exam. But, if particularly they've never had an exam before even if they've been sexually active, the whole exam can just be so uncomfortable for them and so awkward for them that they will interpret that as pain and will tell us that pretty much

everything is painful. And so again we are assessing how are they tolerating the exam, is the exam even just with a single finger at the vaginal introitus do they complain that that's painful. And that's more related to the tolerance of the exam and they're feeling awkward than to a specific finding related to PID or ectopic or whatever else we're thinking about.

The pelvic exam, really an anatomically focused pelvic exam, so assessing if there's any bladder tenderness before we palpate the uterus so if they have a tender bladder you can always have an STD and PID along with a UTI. They can always have a UTI along with pregnancy, they can always have a UTI along with a ruptured ovarian cyst or a torsion. So if the bladder is really tender when we carefully palpate bladder without moving the uterus around, then we interpret the whole rest of the exam in that context. If the bladder is not tender we would assess for any cervical motion tenderness, doing that really gently. The classic chandelier sign where the patient is - it's so painful for the patient that she's described as being hanging from the chandelier. We're trying not to do that, we're trying to be gentle enough that we would elicit that tenderness on the exam before pressing that hard, that it would be terribly painful for her. Sometimes the exam is difficult to asses because just everything is everything is painful for her. And that might well be the case with the PID, that might well be the case with an ovarian cyst, usually if it's a unilateral process it's going to be more tender on one side than the other. But that can also be the case with PID. If we feel a fullness in the adnexal area, our ultrasound will help to delineate what's going on there. And again we avoid - we want to get the information that's important, but we - the more we push the less - the more painful it is for her actually, the less information we actually get. So all of those things can be really helpful in assessing. Endometriosis is on our differential more for chronic pain, and pain with menses, and so our menstrual history would have included how are her menstrual periods, does she have significant pain with her menstrual periods as well, is she on her period now, those sorts of things. Sometimes endometriosis can present with acute pain, sometimes even primary dysmenorrhea can present with acute pain overall. I'm rambling and continuing, is this what you want me to keep going [laughs]?

CK: This has been really helpful to get a sense for how you think about a typical case. Is there a particular, maybe a challenging case, or one specific person that you can think of, where you used this process with them?

E: All of them, I mean [laughs]. The ones - the challenging patients for me are the patients who have acute pain and uterine anomalies that have not been appreciated or understood at outside hospitals and with other imaging. And I've had several of those patients recently. Those are patients where they may present with acute pain, usually it's acute on chronic pain. And the delineation of the anatomy is really critically important. Often they're referred to me because they have unusual anomalies, and those anomalies can be quite complex. So those are patients in whom we would go through all of the steps that I've outlined, but would also really rely much more heavily on more specific imaging and in particular an MRI to delineate the anatomy. Things - unusual situations like cervical agenesis or uterine duplication or even vaginal agenesis as well. So those are things where the imaging is more important than in some of these other situations.

CK: And what let's you know, or how do you figure out when a patient is one of these sort of unusual anatomical cases?

E: Usually on the basis of imaging that - ultrasound, which is our usual first line imaging that doesn't fit with the clinical picture, or doesn't fit with the history. So for example, one of the complex anomalies that I see and have - I've got probably 25 or 30 patients right now with this particular really really

unusual anatomic variant. They - patients with renal agenesis or dysgenesis are quite likely because the kidneys perform at the same time embryologically as does the uterus, if the patient has known renal agenesis and urology's following a whole huge cohort of those patients, often it's even known prenatally because mom gets an ultrasound and the imaging of the baby may show only one kidney. So that's often really known, but the association between the renal anomalies and the uterine anomalies is often not appreciated. So that if the patient comes with that history, then that's a real tip-off that there is quite likely to be something going on with the uterovaginal, not so much ovarian but uterus and vagina, anatomy overall. So those patients often present with a pelvic mass, and what to a really cursory examiner, or on cursory exam, or an exam by someone who's not so familiar with those anomalies, will look like an imperforate hymen, with kind of a bulging mass within the vagina. But the problem is that that finding on exam might be an imperforate hymen if she reports she's never had a period, but if she reports she's having regular menstrual periods then that makes absolutely no sense that she would have a completely obstructing lesion. So a number of my patients have been seen by other clinicians and taken to the OR with a diagnosis of an imperforate hymen, when what they really have - you put together they're having an absent kidney, and the fact that they are having menstrual periods, they have a uterine duplication and a vaginal septum that has a unilateral obstruction. So one side is patent, they're having regular menstrual periods, the other side is obstructed they get menstrual blood accumulating in the vagina, and they get menstrual blood accumulating in the one uterine horn that is obstructed, and then they get a pelvic mass on that side. So that's the common - and they have terrible pain because they are essentially laboring in that obstructed side. So putting those things together with the renal history and the possibility of the anomalies is something that - because I'm quite aware of those unusual anomalies is a diagnosis I am often the first one to make.

CK: And how does your clinical decision-making process change, if at all, when you encounter a patient who is perhaps a bit more unusual versus more the common case that you might see?

E: If she has any other anomalies, congenital anomalies, than my index of suspicion is much higher that she may have genital anomalies. The decision-making for someone - well where do I decide is this - I mean you always have to keep in mind the possibility that this could be an unusual situation, is this just the run of the mill torsion, the torsion that we see probably once every week or two. And I think that the - where the reasoning starts and we start to say maybe this isn't just the usual torsion or cyst pain is with the discrepancies, with the pain doesn't fit with the ultrasound reading, or her description of the pain doesn't sound typical. So I think it's mostly the discrepancies, but with the underlying context that in a teen who typically has never had a gynecological exam done before, or even anybody paying much attention to their periods, we could always have a possible anomaly.

CK: And once you start noticing some of these discrepancies, how do you go about making sense of them?

E: [Pause] So a lot of it comes down to the imaging, in the interpretation of the imaging, and often that's not something that I'm doing on my own. I'm always collaborating with Radiology and I've got a couple of radiologists who are really really good at interpreting the MRIs on patients with complex anomalies. So I will actually consult with them if I've got a situation that doesn't fit with the usual. I'll review the films with - the images from MRI with them because so much does hinge on what that imaging shows. And again, it needs to fit with the clinical picture and the exam as well.

CK: And what role does uncertainty play as you're going through this clinical decision-making process?

E: Wow, that's a wonderful question. I have been trying to find for years, there was an editorial in the New England Journal when I was a medical student in the [time] that I have never been able to find again. I remember reading it at the time, and reading about the role of uncertainty in medical diagnosis. And I think for those of us who have been around a bit recognize that there's often, if not there is at least a possibility of uncertainty always. And part of the challenge of clinical medicine is how do we, how are we are honest with ourselves about how certain or uncertain we are. And I think most of us second guess ourselves a lot, and worry a lot, and think a lot about, could I be wrong with this? Am I missing something? And so always keeping that possibility in mind is important, but important too is how we convey that to the patient. And that's part of what I find really really fascinating and part of the art of medicine, because we have to act in some ways, I mean a patient comes into the ED and I have to make a decision. Does she need to be admitted? Does she need to go to the OR? So to make that decision I have to have some level of certainty. The decision, back to the torsion thing, it's a clinical diagnosis. The ultrasound tells us a lot, we look at the ultrasound, and they tell us about blood flow to the ovaries. And if there is no blood flow to the ovary, then that's easy. It's a torsion, and I can say I'm certain that it's a torsion and be very confident and convey that to the family, we really think this is a torsion, she really has to go to the OR.

If she has good blood flow, then it still can be a torsion. That is not ruling out torsion at all. And because of that, it then becomes the clinical judgement. I have to - but missing a torsion can be devastating for that patient because it can mean that that ovary would die. So a torsion is in a sense a - it's always been described as a clinical emergency that needs surgery right away. I was describing to you the chronic torsion where it torses once and then you may go a month or two or three with no pain and then it torses again. So that's a different clinical entity, but I have to make a decision based on my clinical judgement to go to the OR or not. That's a binary decision. And then in describing it to the family, I need to have established trust first, hopefully doing that from the time I greet them, and as I do the exam, and as I explain to them the findings, and I say family because I'm dealing with kids and of course the patient herself. But I need to convey to them that right now it's my - I've done this a lot, been doing this for a lot of years, sometimes I will say that, although you'll look at me you realize that I've been around for a bit, I don't look as young as I used to [laughs], and they recognize that. But I would say to them that's it's my clinical judgement that this could be a torsion. We think it is, we think that that ovary is twisted. If it's twisted, then it really needs to be un-twisted in an effort to save this ovary. We want to save the ovaries. She's got two of them, so if she lost one for whatever reason, or if for a reason as we're doing the surgery it might turn out that we might have to remove one of them. So I need to separately convey if she has one ovary removed the other one will take over and do double duty, and her changes of getting pregnant are essentially the same as if she had two - probably not quite but pretty close.

But I convey, and saying we need to go to the OR, that this is my clinical judgement. And I need to do it in a way that's not wishy-washy. I think we need to go. And I think it's so important to learn, I sometimes hear my residents, in a sense I think it's a cop-out to say you leave it up to the patient to decide. Now torsion is not a good example of that because - but even sometimes with torsion, the residents will sort of say to the patient, we don't think it is but it might be, do you want to go to the OR? Well that's a crazy question to ask a patient. Nobody wants to go to the OR, but nobody wants to lose an ovary either, so I mean how do they decide, they can't decide that, and that's what you're supposed to do. You're the doctor. So that conveying that this is what I think it is, but it's possible that it's not, so if I'm wrong we'll have a good look around, you know if it's not twisted, we'll look to see what is causing the pain. Often the reason it's twisted is because there's a cyst there, I'll have to make a judgment, does the cyst look worrisome, does it look like I need to take out that cyst, does it look like I need to aspirate that cyst? Might it even look like I need to remove that ovary, and that's a clinical judgement that I have to make,

and I'll have to make that while your daughter is asleep. But conveying that on the basis of my experience and my judgement even - and explaining what it is that makes me think that this is what's going on.

CK: So how do you decide then when you have enough information to then make a decision like that?

E: With torsion, it's in my mind, is it better than a 50-50 chance that this is torsed? And even if it's only 51% likely - sometimes in the past, there's been nurses that I've worked with in the OR, who before we do the case will ask, well doctor what do you think? Is it torsed or not? What percentage, how likely is it that we will need to do more to do - sometimes they're asking about the amount of time it may take, or whatever. And sometimes they're just making conversation, and they're sort of trying to hone their clinical skills as well. And so sometimes we'll engage in that discussion, well I think there's a 75% chance that it's torsed. But it's usually on the basis of how well things fit together. How well the clinical history, how well the exam, how well the imaging, fits with my clinical experience. And I've had a lot of clinical experience with torsion. And a lot of clinical experience with torsion in teens. So that's what I'll put together, the past cases, the cases that I've been wrong. What did I learn from that case? If we took her to the OR, which I never do lightly, that's always a serious decision, even if she's otherwise healthy but particularly if she's not, particularly if she's got other medical problems going on. It's not a decision to take lightly, but if it wasn't torsed, what was it about the history that was different. How can I learn from that situation? And if a similar patient presents again with whatever it was that was different about this patient, that I should have paid attention to that I didn't, I'm going to put that into my equation, into my algorithm, for the next time.

CK: And what role does basic science mechanisms play as you're thinking through your diagnostic process?

E: Again a great question. A lot. And I focus on this with my residents. So particularly with torsion. For example, and we're trying to rule out torsion, but if the patient's last period was 3 weeks ago, and they have a - my brain is giving me a quick brain blip here. If the characteristics of their cyst on ultrasound are not just that it's a simple cyst, but it's a complex cyst, a little bit of either solid or material that might be clot. And she's three weeks from her last menstrual period, then that fits with the corpus luteum cyst, and she has regular menstrual periods, she has monthly periods, she's in the second half of her menstrual cycle, she probably ovulated last week, she's got a corpus luteum. If you have bleeding into that corpus luteum cyst, it's very painful - it's in an enclosed space - but that's the basic science of the menstrual cycle. If she's got a - if her last period was 3 weeks ago and she's got a simple unilocular 4 centimeter cyst, that shouldn't be a follicular cyst if she has regular menstrual periods because she's in the second half of her cycle. And a follicular cyst should go away with ovulation and the second half of the cycle. So maybe that's not even a functional cyst, maybe that's a dermoid, maybe that's a small serous cystadenoma, benign ovarian neoplasm even. So that awareness of the underlined physiology is just critically important, and it's part of what I teach my residents and talk to students about too - is knowing that basic physiology is really important.

CK: And what do you see trainees struggle with the most?

E: What do they struggle with the most [pause]. Of the things they struggle with is teenagers, and the calibration of teens, and talking to teens, and trying to honor principles of confidentiality yet needing to get information and how do you - what do you say to the parents to get them out of the room so you can ask the confidential questions that you need to ask about sexual activity. So that's something that

early-level residents or trainees kind of struggle with, but get a chance to practice a lot. They struggle with that. They struggle with ovarian pathology because it's hard. There are so many neoplasms, and what is a functional cyst anyway, and depending on what kind of basic science education they've had or how much they remember about basic science, they may not have had a focus on the menstrual cycle. And so just bringing that basic science to play in a clinical scenario is something that they need to be reminded to do and to think about. They're sometimes upset with me and my fussy-ness about that identifying data that I want them to tell me first off - the age, the gravidity and parity, and LMP (last menstrual period), and contraception, and sexual activity, and chief complaint. And I will often stop them and make them give me that info in the first place, but then I try to bring it back to this is why I'm thinking about all these things. This is why I need this data to be able to think about the rest of the details that you're going to tell me about, because we do need to think about the physiology, we do need to place the pain in the context of the menstrual cycle, we do need to place it in the context of sexual activity or not.

CK: And in terms of the unusual case that you brought up before, what would a trainee in your opinion struggle with the most if they would have seen that kind of case?

E: Again, these are great questions [laughs]. They would struggle with the embryology and thinking about and - even just the knowledge base that puts even renal anomalies in the same bucket is as mullerian anomalies to really know be on the lookout for those genital anomalies when there are renal anomalies. They may never have even heard of - some of my early-level residents who haven't spent time with me in adolescent gynecology may never have heard of the obstructed hemivagina with ipsilateral renal agenesis, the OHVIRA syndrome. They just haven't encountered it yet. And so it's - if and when they see the patient, and they learn that that's what the case is, they will hopefully forever associate that anomaly with that particular patient and some characteristics of that patient, and how old she is, and maybe what she looks like or what she told them about what she loves to do and her passions are. And you know that patient then will be the association for the resident who has not yet met a patient with that particular diagnosis. But I think that's what makes it stick for them is having that association - one of the things that makes it stick.

CK: What other things help it stick?

E: Repetition helps it stick. The more they are able to see in the decision-making process around a torsion, I'm - several of the residents that work with me now know the scenario well enough, they've worked with me long enough, that they'll give me the spiel about the patient with the identifying data. And then they'll say, bottom line is I think she's torsed, I think we need to go to the OR. So they have really learned that clinical reasoning and decision-making on the basis of previous patients.

CK: And what role does your relationship with the patient play as you're going through this clinical decision-making process?

E: Always important. Patient needs to feel that she can trust me, that I am someone who can help, that I'm someone who honestly is not new at this. And so sometimes families, often families are more willing to address me than the resident, so that relationship is not something that - I mean I guess I've earned it with my gray hairs and wrinkles [laughs], but it's - they attribute that to me. Sometimes they just attribute wisdom to me because I'm a physician, and patients who may be a little less medically sophisticated may do that more broadly to all medical personnel. Sometimes it's the opposite. Sometimes they may have had a bad medical experience in the past, and they approach things from a

very skeptical kind of perspective. Being able to read that, asking the right questions to find out what are their misperceptions based on why are they skeptical. I'm straying from what the actual question was, remind me what this one was [laughs]?

CK: No worries [laughs]. What role does your relationship with the patient play as you're going through your clinical reasoning?

E: I have patients that I follow for a long time, and the ones with the complex anomalies that I follow for a long time, in that role over time, makes a lot of difference. But often these - the scenario of the patient with acute pain, often I don't have a relationship when we begin. I have to quickly establish that relationship. Honestly some of the things that I have been teaching in [course] have been important to identify specifically. Some of them are things that I've always done. I've always introduced myself to the patient, but formalizing it in teaching it to you guys from day one has made it so that there is never a situation now when I wouldn't first introduced myself to the patient. So the teaching that I do has helped me to do those sorts of things that I think I've mostly always done, but now much more aware of, that really do help to establish the relationship. And often especially as I say with the acute pain, it's establishing the relationship, it isn't a previously established relationship that you have that capital to dwell on. You have to pretty quickly establish that trust and relationship. And the statements that I make, you know she's got a good team to take good care of her. She's anxious about having surgery, everybody is but here's the team, it's the anesthesia doc, it's the nurses, it's the team, we all are here, right now all we're doing is taking care of her in the OR. It's - saying those kinds of things help to establish the trust. But yeah, they have to agree to what we are recommending.

CK: Another - any particular cases where you felt like having that trust played an important role?

E: [Pause] There was a really - this is not in the setting of acute pain or the ED. There was a patient we saw yesterday in clinic and her mom was just really really challenging, and just really really hard. And I was trying to keep my - not so much keep my temper because I don't really lose my temper with patients. But I was specifically speaking really slowly and distinctly, and then mom started accusing me of being patronizing to her. And that felt even worse, and it just escalated. And then, I think it was probably a little bit of humor, and I'm going to - I should debrief this a little bit more with the resident that was with me. And we did right after the situation. But I think that there was a little bit of humor that helped us to kind of diffuse the situation, but she was just so challenging. She ended up - we ended up talking for a long time. And it was a visit that was scheduled for like 15 minutes, and we ended up spending like an hour with her because she needed it, and we needed to be able to move forward for her daughter. But it was mom who was being really really challenging. It was a lack of trust initially, and I think we got beyond it where they were willing to accept our recommendations and assessment overall. But it's hard in the middle of it. I just felt like, oh my gosh, what am I going to - she's so pissed at me [laughs]. But yeah that comes up.

CK: And what role does reflection play in your clinical decision-making process?

E: Well, I may not have said the word, but it is the process by which I learn. And not a day goes by that I don't think about the clinical decisions that I made during the day, and dwell on them, and sometimes ruminate on them [laughs]. What could I have done differently? What work in this situation that I'm really pleased worked? That's why I'm saying in - this mom who was so upset, I want to reflect on it a little bit more with some help from the resident because it was so upsetting. It was upsetting to her, it was upsetting to me, I'm glad the mom was mad at me and not at the resident. But that's yeah. That's

reflection. That is - I've got to learn from all that I do. I can't just be doing by rote. And there's still plenty for me to learn.

CK: And how does the process of reflection actually look like for you in practice?

E: It's mostly kind of running down what sticks in my memory from today. It's part of the process of transitioning to home. I don't usually have much of a commute. Some people use their commute to do that. My days in clinic in [place], I do have like a 20-25 minute commute. And sometimes I use that time to just run through in my head what sticks in my mind from today, either that I'm so gratified it works so well that we did X or Y, or sometimes it's sticking in my head because man, it felt really bad that this mom was so angry at me, calling me names, it really just felt terrible. But I feel like I need to address that in my mind, not to - to understand it better, to think about my own reactions, but also to be able to learn from it, but temporarily set it aside when I go home to be with my husband or family. Because I can't keep dwelling on it, although there are sometimes when I can't not, situations that are really really hard. I do dwell on and bring home to a greater extent than I might choose, that I can't quite get over so easily. But most of the time it's I need to learn from this, but here's what I think I've learned, and here's what I think I'll do differently or - keep, stop, start [laughs] for the future. And to kind of in a sense wrap that up at the end of each day.

CK: And what has helped you the most in terms of developing your style of clinical decision-making?

E: [Pause] I have no idea. [Laughs] I don't really have a good answer to that. I mean I've had really good teachers along the way, good mentors. I've worked with some excellent clinicians who - but less the clinical decision-making than how to establish a relationship with the patient. And I've said how important that always is, I think that the example and the thing that is helped is being able to establish that relationship. If I've established that relationship, I'm really caring about the patient. I'm thinking not just this is a job, but that they're relying on me, they're trusting me, and I need to continue to earn that trust. So yeah. And the other things that I think about, I don't think - I think internists think and talk a lot more about clinical reasoning than do those of us who are in surgical specialties. I'm in a hybrid specialty where some of what I do is medical, and endocrinologic, and endocrinologists are a thinking specialty in many ways. But I'm also a surgeon, so I think internists talk and think more about clinical reasoning. So as I have learned more about teaching and have thought more about how do I teach clinical reasoning, thinking about it in a specific way has been helpful to me, to be aware of what my own processes are, and what those - what students need to learn to do over time. I mean I still feel like I'm still learning about clinical reasoning. But that it is - even a concept that - it isn't inapplicable to surgical decision-making, and they talk about the decision for a torsion, which is such a good one. I think it's a good example of how I use clinical reasoning. But I was afraid when I was reminded that you are on my schedule today [laughs]. I was afraid that you were going to hand me a scenario to think and talk about, that would be unfamiliar to me. What you're doing of course is so much smarter and so much better [laughs] and I hope you're going to get much richer data from it. But it shows that I think of clinical reasoning in an internal medicine context. It's not. So thank you for reminding me about that.

Medical faculty 6 (internal medicine)

CK: So, as you probably know by now, the purpose of this interview is to really get a sense of how expert clinicians think through their clinical decision making process. And so when we say clinical decision making, this can be diagnostic reasoning, labs that you would order, it could also be therapeutic reasoning, so really the whole spectrum of what you would be doing in clinic. And so to give us a sense for what the process would look like for you, we would love if you can go through a specific patient case and take us through every single step that you made from the moment that patient came into the clinic.

E: Ok. Let me think...

CK: Definitely take a few minutes.

E: Yea, yea, no [laughs]. And so I don't work in the clinic ever. I have not worked in a clinic since 2008. I only do in-patient medicine now. So I can take you through an in-patient or I can reach back to 2008 and do a clinic patient. I was making the remediation exam for [course] last night, and so I was using a clinic patient from 2008 that I remembered so I could do that one. [laughs] I would also be happy to do - it was an interesting case from about a month ago that I saw in the hospital.

CK: That's perfect.

E: So, I do think when thinking about clinical reasoning and diagnostic reasoning and therapeutic reasoning, I think it's important to put out there that for the most part I think the cases we remember and reflect on, we're probably using slightly different reasoning than the everyday cases we forget. And I can talk more about that later. This one is a more memorable case and so I think it's why I remember it, but I also suspect that the reasoning was slightly different because it was memorable.

The patient was in his early 70s and he presented to the hospital after a fall. He didn't have any strong reason to actually even be admitted - he didn't break any bones, he was clinically stable. But his family was very very worried about him because he had had a series of falls, and they weren't entirely sure why and the patient was very concerned as well. The family really wanted some answers as to why this was happening. And, you know, doing an interview with the patient he had many different somatic complaints that didn't seem to necessarily completely fit together. He was a very long standing diabetic with clear peripheral neuropathy, but was also complaining of general fatigue and weakness, which in elderly patients is just extremely common. It really didn't help to point too much of anything. And so his exam was non-focal other than the known peripheral neuropathy. So we did our exam and yea it was pretty much what we would expect. And so we weren't getting a lot of clues there. And I think what stood out with this patient was when you combined the history of someone of who was worried about the fact that he was losing weight and losing strength, and he was a very intelligent guy, he was actually a physician. And he had worked very hard to increase his protein intake and increase his food intake. But when you looked at his laboratory values, he had several laboratory abnormalities that were just – you wouldn't necessarily expect.

And so he had very low albumin, and he had an elevated INR on his lab values. But he seemed to have intact hepatic synthetic function. And so you know discussing this with the team, it was interesting because we see that pattern not uncommonly in older folks who for example have a malignancy or who are not able to eat. And so we will see those same patterns, but that was clearly not this guy. So really when you take a step back this isn't someone who is dying of cancer or who's been in the hospital for a month not eating and getting antibiotics. This was someone who was supposedly doing pretty well, was

a very functional robust guy. And so we were able to - essentially the way I thought about it was I was really worried that this guy had a malabsorption syndrome, which to be perfectly honest with you is pretty uncommon. We don't see a lot of malabsorption syndromes, certainly not in the in-patient world because they usually aren't bad enough to ever get someone admitted in the hospital. So it is an uncommon diagnosis for us to make. The challenge of the actual case wasn't necessarily making that diagnosis, it's a fairly straight forward diagnostic to make, the challenge is so much in modern medicine was trying to meet the patient's expectations and desires and search for certainty with what we're able to provide. So interestingly, making a diagnosis of what we thought was happening with him which was pancreatic insufficiency takes about 2 weeks because that's how long the labs take to come back. So you just have to sit there and do nothing for two weeks waiting for a single lab to come back, which is a stool acetate.

And so we waited. We told the patient we can't keep you in the hospital for two weeks just waiting for this lab test to come back, so there are a lot of challenges and back and forth with that. But ultimately that is exactly what he had, and he has since been getting better. So thinking about the kind of reasoning which went into that, which I know is what we're here to talk about, I think what really stood out to me with that case is I think my residents, who are excellent, to them they're so used to seeing that pattern in the lab values in an elderly patient that to them it's like, what are we so worried about, that's an unlikely diagnosis because it just isn't very common. And I think what stuck out to me a little bit is the subtleties is yes I see that pattern a lot, but not in someone who is clearly as good a historian, who can tell me exactly what he is eating, and tell me how much he's really pushing to increase his food intake. Those two things really didn't fit with the pattern we were seeing, and I think that is ultimately what gave us the breakthrough to say, oh we really need to think outside the box a little bit. Because he wasn't coming in with the common complaints you see with people with malabsorption syndrome where they get a lot of GI upset. He didn't really have that just wasn't absorbing nutrients correctly. So that was kind of how that case resolved. If that's helpful.

CK: Mmhm. And looking back, what do you think were the critical decisions that you made?

E: Um, I think there was a couple. I think the decision to, this sounds sort of callous, but to really hear him out, I think was really helpful. It's very - when people have a series of vague complaints but don't look acutely ill, it's very easy to just tune out as an inpatient doctor and say, I hear that you're suffering but you're not suffering enough to be in the hospital, so you know [laughs]. You know, so I think with this gentlemen to really say, wait this is someone who is really struggling, he's really worried about the fact that he's falling, he really thinks he's well off his baseline, and I think as an inpatient doctor it's something that we struggle with all the time, which is we really don't know how people are doing a week prior to their admission. We see people in the arc of chronic illness, and you don't know where they are in that. And you don't know whether the very debilitated state that they're in is where they're going to be and where they've been - or whether this is really a big change.

And it's surprisingly hard to figure that out sometimes. And with this guy, I think really hearing him out, as this was a very functional individual who had really fallen down rather abruptly in his functional status, and he was really trying to get us to hear that. I think just listening to him was really important and then combining that with the - and looking at his lab abnormalities and just say, you know the story that you're telling me really doesn't fit the lab abnormalities that I'm seeing. They just the two of them don't add up. To me that was the real critical thing. Beyond that I think working up a malabsorption syndrome isn't - I mean you can just look that up [laughs] "malabsorption syndrome" and then read about it. I mean I happen to know how to work that up, but I think for someone - even without having

that particular expertise, you can always just look that up. But it's more knowing, hey wait I gotta put a pause here. This isn't adding up. I need to think about why someone might not be absorbing their nutrients. And then there are the little things thinking like, you know for this gentlemen he had an elevated INR, which means that you're worried that he's malabsorbing fat because vitamin K is a fat soluble vitamin. And so we're putting that sort of line of reasoning together is helpful. Along the same lines we diagnosed him with a copper deficiency, with can also contribute to neuropathy. Copper deficiency, I just happen to know it looks a lot like B12 deficiency. I suspected it probably wasn't playing that much into his neuropathy, which is probably chronic from his diabetes but those are parts of it that I guess we would look into. But to me, the real key was pay attention to what he was saying and then really trying to see if the story he's telling fits with the lab abnormalities we're seeing. And it didn't fit, so we knew we needed to look or think a little bit deeper about what was going on.

CK: And how do you know whether something fits or not?

E: I think that is the harder part, and in fact again, it's not me trying to be like, oh I was so good. But my residents were really dismissing that. The ER dismissed that, the night residents had dismissed that, my residents had dismissed that. Because, again, we see those patterns very frequently in elderly populations. High INR, low albumin from poor nutrition and poor oral intake or catabolic state such as infection or cancer. This is - what didn't fit otherwise was this is a nontoxic, healthy appearing person other than he was elderly. That idea of fit, there's a couple of things that stood out was the degree was off, so he had an albumin that was less than 1, which is even in cancer is uncommon until people get extremely cachectic, which he was not. And so while I see low albumin every day, in fact, I would say 90 + % of my patients have abnormal albumin value in the hospital. At least 90, it's probably higher than that. But that degree didn't fit. Where when we see it that low, that's like something else, I'm missing something and I need to think about it more deeply.

And I think that's what I mean by pattern matching. The high INR we see all the time as well. Frequently its patients who are hospitalized and on IV antibiotics or have liver dysfunction. And he didn't have any of those. And so then you're really thinking Vitamin K deficiency, which you can see in people who just aren't eating at all - but that also wasn't him. And so again really taking a step back and slowing down.

When I think about clinical reasoning, the way most of us do clinical reasoning in our every day - and this is why I think there's a real difference between the everyday patient and someone like this - is it is very much a pattern matching for when you've been doing this for a while. You're making similar diagnoses over and over again. And you know I do think there really is a degree of, this feels like heart failure. And sometimes we try to explain why it feels like heart failure. I'm not at all convinced that my explanation is accurately reflecting why I know that this I heart failure, you know what I'm saying? Again it's a pattern matching that I may not able to articulate. And I truly believe that for most of these straightforward cases, I do think that we use a separate reasoning system when we get to a case like this where it's not something you're seeing every day. You have to really put the brakes on, whoa whoa you're not fitting into any pattern that I'm used to. Because I don't see a lot of malabsorption syndrome. It's just not a common diagnosis for me. And then you really have to take a step back and kind of go through it step by step. And that's when you say, maybe this could a vitamin K deficiency. Maybe that could be a copper deficiency. Maybe you know, your albumin is so low because you aren't absorbing nutrients even though you're eating them. Now let's sit back and do like we do in 2nd year of medicine [laughs] and say what's your diagnostic framework for that. And to really slow down. That's like a once a month or a once a week phenomenon as an inpatient doctor. Where everyone else you're like yup pneumonia, yup it's a UTI. Because it just fits, and you get that - you know it within 2 seconds if you're in the story.

My friend believed in that - especially for diagnostic reasoning - the majority of it, it almost becomes rote for someone who has been practicing for a while. But the important thing is to recognize when it's isn't, and to figure out when to slow down and listen to the story again, reflect again, think about what you could be missing. And then do a step-wise approach to it. I firmly believe that's what most of us do, even if we don't know that's what we're doing.

CK: And what tips you off that it's not the everyday case?

E: Well it can be a couple different things. Probably the most important thing especially as an inpatient doctor that it's not an every day case is when they're not responding the way you think. You say, oh this is clearly heart failure, we just need to diuresis them, and then oh that didn't work out [laughs]. That didn't make them pee, their kidneys got worse, oh. So I think probably the most common way it comes up is we were wrong. We think we knew what it was, we start treatment, and they don't get better in the way that they're supposed to. And then we rethink it. Or you know we start treating them for something and something else isn't getting better, and you're like oh I might be missing something. I would say the most common way is that patients don't act the way we expect once we start treatment, or we're observing them thinking that XYZ is going to happen. You know like if I diagnose someone with an aspiration pneumonitis. There's no specific treatment for that other than time, but if the patient keeps getting worse or things are changing in a way that I don't expect. You know say 48 hours after an aspiration event, I wouldn't expect them to have a new fever. So if they did I would have to say oh perhaps that was not an aspiration event. Or you know there's many different things, but it would make me really stop and reflect on the case when they're not doing what they're supposed to be doing based on my diagnosis. I would say that this is far and away the most common thing.

But then we also get other cases where you - what you're used to if you've been practicing for a while is the diagnosis hits you in the face. Again within a few minutes of hearing the story you're like, yeah I know what this is. And so it really strikes you when you're going through the story, and you're like I don't know what this is [laughs]. You really get that feeling oh I really gotta take some notes here - you really start thinking more deeply because you're not getting that feeling of I know exactly what this is right away. So I think it's both of those, but the more common one is that we're wrong. We think we know what it is, and we find out we're incorrect [laughs]. Because - and that's why whenever I'm teaching or talking to students that's why I say it's so important that we really - you get a sense of and this is what you unfortunately only really get from experience - which is how does this disease behave. What is the variation of how quickly they get better, how should they feel as they get better, what do we expect to see as they get better. And then to know when they've deviated from that path. Because that's when we need to stop, and say maybe we weren't wrong but maybe there's something else going on. Or maybe we're missing something. Or maybe we were totally wrong with the diagnosis in the first place, and we need to rethink it. I think that's often hard as well for patients to understand. I bring this example up a lot because I've heard it so many times. If you ever get to meet a patient who's been diagnosed with lupus, you will frequently hear a similar story, which was I kept going to doctors and telling them I felt bad, and none of them - they all missed the diagnosis. And sometimes that is clearly the case. The doctors missed the diagnosis.

But frequently with a disease like lupus, in order to get the diagnosis you have to have a certain number of problems. And frequently what's happening with these patients is they're going to the doctor, but they only have one or two problems. They literally have to wait to get bad enough that we can make the diagnosis. You can't make the diagnosis when they're just fatigued. They don't meet criteria. It doesn't mean there's nothing wrong with them, but they - if you try to diagnose them with lupus, and all they

had was fatigue, you wouldn't be a very good doctor [laughs]. But we're not very good at explaining that to patients, and so what they walk away with it is [you] did a terrible job diagnosing me, when actually you did all the things right medically. But where we are in modern medicine is we can't diagnose lupus when all they have is fatigue. They have to get some kind of joint problem, they have to get the other syndromes, and so you know I don't think we do a very good job of explaining to patients that diagnosis is a continuum. And you can't - we're not good enough yet to diagnose people right when they want to be diagnosed. Sometimes we have to wait a little bit.

CK: So going back to the malabsorption case, what other diagnoses were you considering?

E: Um, for him, we were - what are some of the other things that we were thinking for him? So probably number 1 when we first saw him was could we explain this from cancer. Could this patient have a widespread cancer, could he have a gastrointestinal malignancy, and he's just isn't eating like he says he's eating you know. So is he having more of an anorexic kind of syndrome, so he has no appetite, he's refusing to eat, and he's just telling us. You know we spend a lot of time listening to patients, and we often know that the stories they tell us are frequently inaccurate. So we spend time corroborating with family members who are watching him eat, so we were worried about that. I was definitely worried about again a malignancy. We thought a lot about an occult chronic infections, so things like osteomyelitis can definitely mimic this. The INR would be a little atypical but certainly the low albumin, where it's sort of a wasting state from chronic inflammation. And then we thought about other malabsorption problems. There was actually for adults there's fewer than you would think, but there are a few other ones that could have fit with him. We actually tested him for celiac disease, which he didn't have but that would be of your malabsorption syndromes, it would be one of the more common ones. A little atypical to present at his age. And the last thing we considered because he also had a lot of complaints with neuropathy, which we thought was pretty well explained by his diabetes plus minus the copper deficiency. But again looking for a paraneoplastic syndrome, which can also cause a peripheral neuropathy so we did do a workup for that as well. Just to make sure we weren't missing that with the help of our neurologists.

CK: And what role did your relationship with the patient play in your clinical decision-making process?

E: You know, it was interesting, I think for - there's a couple different things going on with the patient relationship. He was someone who because he was trained as a physician wanted to have a lot of control over his care and everything about his care. I think he was a pretty good example of because of that need for control, he probably ended up getting worse care at least in the outpatient world. This was someone who was seeing doctors frequently. And this had been going on for years. This was not a new problem. You know this had really been going on for years. But my general feeling was that because of his need for control his physicians took care of the things he asked about but didn't look into the things he wasn't interested in. You know and I think that comes back to that role of every clinic visit needs to have two agendas, which is what does the patient want to get out of the agenda but what the physician's responsibility is to look at the patient's overall health and to think about the things they're not thinking about. You know, if a patient comes in for a URI but they haven't had their pneumonia vaccine, the patient that day is not interested in the pneumonia vaccine. But they are interested in not dying of you know pneumococcal sepsis. I'm interested in that, and they are too they just don't - it's eating your broccoli, you're not thinking about it that day, it's a long-term thing. And at the end of the day it's the physician's role to think about that, and I think his relationship with his physicians was such that they were always focused on whatever he was interested in that day but took a hands off approach to everything else. So they weren't looking at some of these other problems in a way they could

have. And I think again it had a lot to do with his relationship. With us, he was so adamant on getting answers because this all could have been done in the clinic. There was no reason he needed to stay in the hospital to get some of this, but he was so adamant about it that we did the workup for him while he was there [laughs]. And that really came a lot from him being unwilling to complete the workup in the outpatient world. And so we did it. Which I mean doesn't hurt me none, these are serious questions I think for the broader healthcare system, which is if patients have preferences that are much more expensive but it's a preference, how do we take into account their preferences but also not ignore the fact that what they're asking for is considerably more expensive than what we're recommending. I don't know how to fix that [laughs]. But he got a workup of pancreatic insufficiency that probably cost $150,000 when that could have been done in the clinic for $5. And we're all paying for that. It's a little depressing to me, but that is what it was.

CK: And what do you think - it sounds like from what you said that this patient had a different sort of relationship with previous physicians. What do you think made the difference between you and him?

E: Well I think it's always - as an inpatient doctor I have the disadvantage of not knowing most of the patients I take care of. I'm meeting usually for the first time when they get in. You know there are some frequent flyers that I know, but as a general rule I'm like hey we're just meeting right. That works against me and I don't have a personal relationship with them, I don't know their background, I have trouble knowing what their baseline is, things like that. The flipside is, the huge advantage is, it's a fresh set of eyes. It really allows me to do a pause and say, woah woah what's really going on, whereas I think if you're seeing someone every day in clinic you may not see some of the more subtle changes that are happening. Problems can grow without maybe you noticing them because you're seeing them so frequently. You can get caught in, oh I know what's going on, and there is no built in pause button, whereas for me it's a fresh set of eyes, it's a new take on a case, which - it's like getting a second opinion. I can be a second opinion as the inpatient doctor and say, woah woah are we really doing that? And I think - so again it's a good and bad. To me I think in medicine, especially when you think about diagnosis and treatment but really diagnosis, there's a huge value to second opinions. You get a fresh set of eyes looking at the same thing, do we meet at the same diagnosis or do we go in different ways and now we should talk about the case. I think there's a huge room for that in modern medicine, which is to have more second opinions. And then what we're probably missing more than anything is having physicians talk about how they're seeing the case differently and understand each other's perspective. I think that piece is largely missing. Unfortunately usually what ends up happening is the patient goes with the answer they like better, which is not the thoughtful or really useful approach to getting a second opinion. But that's frequently the way it plays out.

CK: And what role does basic biology mechanisms play in your clinical decision-making process?

E: I thought about this a lot because of exactly this project. I often think that - cause I really enjoyed my basic biology a lot and I was a biology major in undergrad and spent some time doing research before going to medical school. I think I probably certainly use underlying biology and biology principles perhaps maybe even more than some physicians. I obviously don't have a great scale for that, but I do think that it does inform me. Far and away the things that are most informative is actually basic physiology. And then when you think about pathophysiology you're really thinking about how diseases make that basic physiology go awry, and so I think about cardio pulmonary physiology and the basics of that all the time. Do I think about molecular mechanisms? I would say that in terms of diagnostic reasoning probably a little less frequently but still there. The stuff that I really need to know to make a diagnosis is frequently not molecular. It's relationship of hormones and you know if you think about

Vitamin K deficiency and the fact that Vitamin K is fat soluble. That sounds mechanistic, but really it's an isolated fact in my brain that I just I happen to know that. I'm not like reasoning through, like thinking about the structure of Vitamin K and how that would make it fat soluble. It doesn't look like that. It's just a lot easier to remember the factoid that Vitamin K is fat soluble than to really - I don't have a picture of Vitamin K in my head, I don't know what it looks like. So I'm not reasoning from that really basic science thing. It's not that useful. But the basic physiology is hugely useful. So I do think that it's important. It's clearly more important for these challenging cases than everyday cases if that makes sense. Again, I think the everyday cases, you're almost going it's pattern matching, it's feeling. When you think about how pattern matching works, it works through feelings right, it's happening at a subconscious level and then this *feels* like the diagnosis. This *feels* like the right way forward and again it's pattern matching through experience. But that's ultimately what it is. You're not necessarily - when I go through the reasoning it's more posthoc. I'm explaining why I feel that way, which I can use molecular arguments for it. But ultimately that's not what was happening in my brain that got me there, at least not in the traditional sense. But I think with these harder cases where you sit and slow down, I do think that again, at least physiology plays a big part in it. Some of the molecular pathways probably less so. I don't know if that's what you're trying to get at but I'm happy to...

CK: We're trying to get at whatever you think about, so that's perfect. I know the concept of more of an everyday case has come up a few times. Can you give us an example of an everyday case that you've seen recently?

E: This one is harder because they frequently - they're everyday [laughs]. Let me think for a minute, what is a good everyday case? [Pause] Well I can think of a couple that again they're [place] cases so even though I'm calling them everyday cases, they may not be totally everyday. But I thought this was a really interesting one. It was a younger gentleman. By younger he was in his mid 40s. And he had a bicuspid aortic valve that had been replaced with a mechanical aortic valve in his early 40s, so a few years prior to admission. And he, because of the mechanical valve, he had been on coumadin. And he had come in with a severe headache and had been found to have subarachnoid hemorrhage from being super therapeutic with his INR. And at least as far as we could tell, he had been coaching soccer and had been heading the ball. And we think with a very high INR and just even that little bit of trauma that had caused him to have a small hemorrhage. Straight forward case. There wasn't - it was like yup. That's what happened. You know we spent time thinking about was there any other trauma, why was his INR out of wack, like what was he doing. So there were still pieces of that where you're trying to make the diagnosis but at the end of the day it was like you know pretty straightforward. To me the most interesting thing about the case was I was also coaching soccer for this past quarter, and to coach now you actually have to take a CDC approved module on diagnosing concussions in your kids. And I had been up very late because I had to finish my coaching certification watching that video, and he had been up very very late watching the same video. And it was then that it dawned on him that the fact that he was having this severe headache was abnormal, and then he went to the ER to get diagnosed. I was like, you were watching the video? I was watching the video! [laughs] We had a wonderful time bonding over the fact that we were watching the same video. His had a different thing to it, but it was really good that he actually came in and got the appropriate diagnosis before things got worse. So the concussion video really helped him maybe not in the way the CDC had planned for it to help him, but it really did help him, it was wonderful. But again, the diagnosis there wasn't crazy or hard. You had to put together - and this the ER largely did, which was here's this gentleman who's otherwise healthy but has this aortic valve condition, which causes him to be on blood thinners, and oh man his blood's too thin, and he's got a severe headache, we better look at his brain, and oh there's blood on the CT. You know what I'm saying that reasoning is not - at least if you've been practicing for awhile - that just seems so obvious. You can't

- it's hard for you to understand how someone wouldn't do the same thing. And that I think it happens a lot with clinical reasoning where when you've been doing it for a while, it's like you can't understand what it's like to not know to do that. Cause it just seems so obvious. But obviously maybe a lay person may not, but it seems very very obvious. So that was one where you know the diagnostic reasoning wasn't hard. Thinking about the more challenging parts of medicine, the hard part is well what do you tell this guy? Can he not coach anymore? Can he not play soccer anymore? This was actually part of his livelihood you know. He was luckily not going to have any long term disability from this, which was great. He recovered really well, he didn't have any at least measurable deficits from our end. How do we help him to manage his INR better? Cause that's really more of a resource question than a medical question. If you have lots of resources, you can check your INR at home. How much of it could really be explained to him, the foods to avoid, the you know how important this is to check. There was a language barrier with him as well, which made it hard. There were a lot of these things that made the case hard, but not from a diagnostic or therapeutic standpoint. That was really straight forward. He needed to stay on coumadin cause otherwise that was you know, his valve would clot, so in terms of the traditional medical decisions that we think about that I think students a lot - you're worried about making the wrong decision there. Whereas with this one, everybody would have gotten those decisions right. The harder part actually was like the patient counseling. And to really get him to participate in thinking about how he's going to help himself and how he's going to stay safe. And that was actually where the challenge was. But the rest of it was really straightforward.

CK: And with the malabsorption case, what do you think a trainee would have struggled with?

E: I think for a trainee you know this was where my trainees did struggle, was that debilitated older person whose falling is really really common on the inpatient medicine wards. And for the most part, there's not a lot to diagnose, and unfortunately there's often not a lot for us to do. You know frequently it is a consequence of getting older. It's a consequence of really the debility that frequently comes with age or with other chronic medical problems. You know this person had pretty bad diabetes, and so it's like um. And so I think the challenge for the trainee is to say I see a 100 of these patients and 99% of them there's nothing major to do or to diagnose. It *is* straight forward. And the hard part is knowing who's that one person where you need to pause and kind of remove from the pile and say, wait this one's different. Why is this one different? What's special about this one? We need to dig a little bit deeper. I think that's what my trainees were struggling to notice is to them he *was* fitting a pattern but to me he wasn't. They thought his lab abnormalities were consistent with his diagnosis and his story, and I felt that they weren't. And I think they had trouble seeing the difference between those things.

CK: And how do you think people learn to be able to pick up on those subtleties?

E: That's a really good question. I love just to say it's experience, but when I think about learning theory, one of the examples that I love to give is this idea that you can have a lot of experience and still not get better at something. Right, and a great example I always give for myself is playing pool. I've probably spent thousands of hour playing pool, I haven't played in years, but when I was younger I used to play. And I am convinced that I am no better today than I was literally the first time I picked up a cue. There has been zero, despite the experience, there has been almost no improvement. And so, I think about this a lot in the context of learning. What is the difference? You know people talk about this idea of deliberate practice. On that there probably is a role for how you structure your experience such that you take away the most from it. I can think of some certain things that we can do within medical education to help people to learn from experience. I think a lot of it is getting feedback on when you were wrong, paying attention to people's course so that you say, Oh I was wrong back there. Reviewing old cases so

that you think you were right and you were like high-fiving, and then you're like no, no I was wrong, things didn't turn out the way we wanted. I think about this a lot, I paid attention to this a lot when I was training, which is the challenge of being an emergency room physician. Unless you're really dedicated, you can get into practice patterns where because you don't see the outcome, you just always assume that you're right, which again gives you experience but actually can reinforce bad habits. And so I try as much as I can to follow up and get follow up on my patients, so I can learn when I was wrong to hopefully make experience into a learning system. Learning to get better as opposed to literally learning to reinforce maladaptive or bad practice patterns. Could I do better? Yeah. I'm lucky that by being in an academic center, you're forced to reflect more on the cases, and so you're forced to learn from them in ways that I think for the average clinician out there practicing where the goal is to get the work done, taking time to review your old cases is not built into your day or time. And I think there's a real loss in our medical system overall in that we haven't built that in so that you can have someone who is out in clinical practice for a decade who maybe isn't getting any better. They have more experience but it may not have translated, like my pool playing. I played for ten years and I didn't get any better [laughs]. You can very easily see a physician who practiced for 10 years and because they're not getting feedback they need, they may be no better than the day they started. They could even be worse. They could assume they're doing the right thing because they're not getting feedback, they keep thinking yeah and it reinforces that particular pattern. But that pattern was terrible.

CK: What role does uncertainty play in your clinical decision-making process?

E: Well I think as a generalist, there's a huge amount of uncertainty in my practice. So I think compared to other physicians. It's actually something my wife and I talk about a lot because - I talk a lot about it with my students too, which is I think every generalist needs to be comfortable with uncertainty. You're not the best at anything cause you're a generalist [laughs]. That's the whole problem with being a generalist. And that if they're seeing you as a generalist they may not have a firm diagnosis yet. By the time they're seeing my pancreatic cancer specialist, hopefully we know that it's pancreatic cancer. And that person can be up to date on every - all the newest literature in pancreatic cancer. Even though they's still going to be uncertainty because we haven't done every study yet, they at least can be certain that they're following the most up to date research and therefore providing the most up to date treatment for that diagnosis right. I think there's a lot less uncertainty in sub sub specialized care, whereas a generalist there is uncertainty everywhere. I hate the way it plays into clinical reasoning is really that focus on making sure patients are following up on the course that we expect. I know anytime I make a diagnosis that it's ultimately provisional on that they get better the way that I expect them to get better. And you know I actually found a way to talking with patients about that. When I see them in the ER, I think this is what's going on, I think this is how long you'll be in the hospital, how long it's going to take to get better. But if you don't, we're going to have to reconsider that [laughs]. And it's literally what I tell them in real life. I think it rings true to them. I think most patients know that this is ultimately in our - and I even try to reinforce that with them. You know if you get a doctor that comes in here and says they're absolutely sure about something, you may want to get a second opinion cause you should be really cautious about telling our patients that we're positive about almost anything because we will probably be wrong.

CK: How do people - or have you become more comfortable with uncertainty?

E: I'm not sure I was ever uncomfortable with uncertainty [laughs]. I think that's always been - you know I think for myself at least, I can't speak as much to other physicians, if I felt I was uncertain because I was poorly trained, that would make me very uncomfortable. If I was sitting here telling you I don't know

what's wrong with you because I'm not a very good doctor [laughs] that would make me you know - if I thought that there was someone else who could come in and had all the answers, I would feel really bad that I was uncertain cause I was the guy that didn't have any of the answers. I think I've come to the point where I clearly know that I don't know everything, where I clearly know that there's a lot of physicians who know more about things that I don't know. What I can feel very confident in, especially after practicing for a while, is if I don't know the answer it's not necessarily because I'm incompetent. It's usually because there isn't an obvious answer at this point in time, and that we're going to need to get more information. Or I may not know the answer, but I know the right person to get you that answer, which again as a generalist is frequently my job. Like I don't know what's wrong with you, but I got a neurologist who probably does, let me go get him. And so to me, I don't spend a lot of time worrying about that to be perfectly honest with you. It's not something I spend a lot - but then again this is where I am comfortable that the uncertainty that exists in medicine is because it exists in medicine, not in me, if that makes sense. It's because we're in an uncertain field where we don't know everything. I don't know everything, but more importantly *we* don't know everything cause I can go look stuff up and be like yeah we don't know [laughs]. And again I feel pretty good about that. Most of the time I'm sitting with a patient and telling him I don't know it's not because I was lazy or incompetent. It's because that's where we have gotten to in medicine. But I also have the luxury of I have time to go look things up and not every physician has that luxury. I have a team helping me, and so they can go type the notes and I can go read the literature. And again that is a luxury that not every physician has. I was also - I think that for me for better or for worse, confidence has not usually been a problem [laughs]. And again I think that ties in with that uncertainty thing. I have been humbled many many times in medicine, but I have a natural confidence that is just literally is kind of the way that I am. Because my wife and I talk about this a lot where she doesn't quite feel the same way, and so I think she - when we talk about exactly this issue she struggles more with the uncertainty, where it's more again coming from self-doubt. It's I don't know, I don't know what to do here, is it because I'm bad? Or is it because no one knows what to do here? And we talk about the cases, and I'm like oh it's because no one knows what to do and that's frequently the answer. But she often is worried that its because *she* doesn't know, not because it *isn't* known. And again I think that is almost more of a confidence thing. But usually after we talk about it we realize no it's just no one knows what to do here [laughs]. That is what it is.

CK: How about trainees? In your experience, how have you seen them respond to uncertainty?

E: As a trainee, I think uncertainty frequently is viewed almost as a learning opportunity. It's really nice as a trainee to know that the buck doesn't stop with you. You can be like wow I really don't know what to do here. I can't wait to find out what Dr. so and so is going to do. Right? And it's actually one of the best parts about being a trainee, which is I really don't know the right way forward here. I've thought about it, I've looked things up, I really don't know what to do. This is my - and again if you want to get the most out of being a trainee, that's your opportunity to say like it isn't in the textbook, it's not on Up To Date, it's not in any of these papers that I've looked up about what to do here. Now I really get to learn what someone with experience would do. And then ask them about how they came to that decision. And so the best trainees you know really relish that, is to say that I'm uncertain about what to do, I can see both options, and now I'm going to really learn from experience. To me that is the most important thing that you can get out of training because it goes by so fast, and then suddenly the buck does stop with you, and you have to like oh what do I do now? [laughs] And that's the scary part, but actually uncertainty when you're a trainee is almost a blessing. It's those moments that you're looking for because that - if you're doing it right, it's revealing the holes in your education. And so no, I don't think uncertainty is difficult during training. I mean there's always moments when there are decisions

that need to be made in real time. You know someone is unstable or coding and you just need to do something. But even then at least the way it works at [place] is you're calling for help, and you're saying I don't really know what to do, I'm going to do this but I'm calling at the same time. It's uncomfortable, but it's more uncomfortable because it's scary, because someone's unstable. But no, I don't think it's a huge issue for our trainees. That's my perspective, but I could be wrong.

CK: And what role does reflection play in your clinical decision-making process?

E: I think, to me it's something that I've you know - my personal experiences learning from mistakes is probably the best thing that we can do as physicians in terms of growing, and so it's something that I've tried to build into my practice. So if we have a patient who passes away, codes, transfers to ICU, gets re-admitted, any of those things we'll take time as a team to reflect. And so to me, doing team reflections is probably the most important thing in terms of my clinical decision-making but also my growth in terms of improving my clinical decision-making. Having people reflect on - you know you're doing self-reflection but you're also hearing from the team. What were they seeing that you weren't seeing? How were they viewing the case that you may have missed it? And also hopefully inspiring them to get them to do the same in their practice, so I think it's pretty important. I'd love to make more time to do it, especially for some of the cases that get away from me, that are discharged and they don't follow up with [place] docs so I have no idea what really happens to them. Those are the cases where clearly I can learn the most from in terms of reflection, but they don't have a good system for doing that yet.

CK: In practice what does your reflection process look like?

E: What we will literally do is - so if we have a bad outcome of any type, then we'll literally as soon as rounds are over, we'll stop, we'll all get together as a team, and I'll usually just say you know let's spend a minute talking about what we could have done better. I'll usually start with the most junior member of the team just so they can, they have a chance to share their thoughts, whereas if I go to the more senior member of the team or myself, maybe all the thoughts will get out there and the junior member won't have anything to contribute. So if a student was involved in a case I'll have them reflect if not, I'll start with the intern. And we'll usually have them you know really try to sit and think about was there some way we could have avoided that outcome? Did we have the wrong diagnosis? Did we not treat aggressively enough? What did we miss? You know to really spend some time going through that, it's a lot of thinking about the details. I would say again when I think about the difference between a more junior member and a more senior member, it is something that I've noticed that the more junior you are, the more trouble you have seeing the gaps, seeing what we didn't do or what we could have done better. They really do struggle with that more. I even did a, this is 10 years ago, but when I was a Chief Resident, I started a thing where every month the interns would get together, and the point was to reflect on things they could have done better that month. And many of them really had trouble thinking of anything. When I think about the average intern, there's something every day if not every hour that you could have done slightly better [laughs]. I mean really like I don't mean that in a negative way. It's tweaks you know that's what you're doing that whole year is building your style, and a lot of it isn't a decision you made but maybe the way you spoke to someone, the word choice you used when you spoke to someone. The thing you forgot to do like reinforce something you know. There are so many things that we can tweak, but many of them you're moving so fast and doing so much, you have no reflection at all. And then when you ask them, hey how did your month go, what did you mess up? And they'll say, I can't think of anything. And so I think we have this huge opportunity to help them get better at that, and I think the good clinician will do that with some regularity. I know I try as much as I

can to think about - I had a patient this summer who passed away. I really do think we made a mistake, and we all talked about it and thought about it, you know, it's really important.

CK: Let me check my time. I think we covered everything? Let me just double check [flips through papers]. One question I ask, which is just going back a little bit and since we have a few extra minutes. So thinking back to the malabsorption case, how do you know when you have enough information to move forward? So that could be moving forward in terms of treatment, in terms of ordering a certain test, or anything else.

E: That actually fits in pretty well with that case because certainly with a malabsorption type syndrome the - as we were saying there is a definitive test that you send. It can be tough because it doesn't always come back like clearly yes or no, which is really annoying. This one, his did. It was a clear yes, you have the diagnosis, but you're not always that lucky. There is this fairly large gray area with fecal acetase, and so that can be really frustrating when your gold standard test comes back with a huh? [shrugs to indicate uncertainty]. And that can be, those are the really challenging case where you get into that uncertainty, where it's not you are not smart enough or don't know enough. It's that we don't know enough, and then we're really just relying on judgment and clinical expertise because we don't know. And that's where we do like you know therapeutic trials and things like that where you say, let's treat you for a little bit and see what happens. Because we don't know right.

With his case it was an interesting point where we had this - you know we sent the test off, but we know it's going to take a couple of weeks to come back. And so then you come down to the cost-benefit of treating without being certain. And that's something that you're constantly weighing, you know if you're doing this right you should be thinking about that all the time. I have a lot of fun with this during the 3rd year clerkship. So for medicine I run the clerkship, and I had - we do these simulation cases as part of the clerkship. And one of the things I really try to introduce to them is - and when people are really really sick you're often forced to make decisions before you have firm answers, and it's often students first introduction to that. You know the patients are very very sick, you don't have the diagnosis, you're waiting on a whole bunch of information to come back, and so then you really have to start thinking about what's the risk benefit of providing a treatment before I know the answer. Patient's short of breath, is it going to hurt him if I give him some Lasix. I don't know if they have pulmonary edema right. And those are - that requires at least integrating a lot of information about the risk of a treatment, combined with what's the risk to this person in this clinical situation. Am I really going to hurt him that much based on what I know? How likely is the diagnosis that I'm thinking about treating with that potentially harmful treatment? And so it is integrating a lot of probabilities you know at the end of the day, and coming up with some answer.

And the reality is none of us who've been doing this for awhile calculate any of those probabilities you know [laughs]. And so again it comes back to more of a feeling thing, which is that yeah for the most part no one really gets hurt from one dose of Lasix, so the risk is minimal, and the upside is potentially pretty good, so we'll go ahead and give it. And that's exactly what we went through with the malabsorption guy which is Creon, which is pancreatic replacement enzyme, has almost no side effects. Other than you have to pay for it. It really doesn't have significant side effects, so ok just start treating you. Now, you can also argue that the upside is two weeks of absorbing food is better than two weeks of not absorbing food. Again, this is a long term problem, it's not a short term problem. And so are you really helping someone that much by starting them on treatment a week early? The benefit isn't that much, but the risk is almost none so we went with go for it. But again that's really what you're weighing. We thought that our pre-test probability of this being pancreatic insufficiency is very very

high, and the risk of providing pancreatic enzyme was extremely low. And so that equation adds up to go ahead and treat.

But I think we're not always doing it that explicitly. It often ends up - you're almost calculating that subconsciously. You're often not doing it explicitly. That can also get you into trouble sometimes, but for the most part if you've been trained well and you have some experience, usually it doesn't. We do a case with our medicine residents in the sim [simulation] lab, which is a classic case of this. So in the hospital, if you have someone who has depressed level of consciousness, altered mental status, and you call a code or rapid response team, very frequently the first thing that will happen is they will give Narcan. Just say, well I don't know if they took too many opioids, but if they did this will fix that. The downside is often thought to be none. And if you practice for awhile, you might think that's true, until you find out that there is a downside, which is you can induce acute withdrawal in patients who are opioid dependent and that can actually, depending on the clinical situation, actually be dangerous for patients. And so it's a really fun thing where again you have residents who have been practicing for awhile, and who are used to seeing other people do that, and again it's very easy - and this is the challenge of learning through experience - if you and I are working together, and you're like yeah, every time we go see a patient, [doctor's name] just does that, and it seems to work out really well. If I'm not explicitly saying, this is how I'm weighing the risks and benefits, you're just going to be like yeah every time I show up I just give Narcan, nothing ever goes wrong. Until it goes wrong. And so that's why - this is what we do. It may be not be the optimal thing for learning, which is we put those - we calculate the risks and benefits, those of us who know or have experience, and then do something. But if our trainees are just learning through apprenticeship by watching what we do, they may not see that calculation, they may not know who is the person we withhold it from until we're at that case together. And then you go, [doctor's name] why didn't you give the Narcan? And I go, oh they take 300 mg of morphine a day, that would be a disaster. And so that's why I try to design simulation cases that explicitly point out those exceptions, so that people can learn from them. In fact some of us think that's a huge role for simulation medicine, which is to say, what are the uncommon experiences that you might have to practice for 10 years to see once, but that one time is super important because your mistake can really hurt someone. How can I make that happen for you today, so you can learn from it today without having to kill anyone. That's the goal, right? [laughs] And so I try to create cases like that, that I think can help people for that.

CK: Great, I think I'm going to pause the recorder.