

STEM BUILD: An Online Community To Decrease Barriers to Implementation of Inclusive Tactile Teaching Tools

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Access to 3D printing and other “maker” technologies has opened new doors for the creation of classroom activities using physical models. Multiple strategies for implementing 3D-printed models exist, and work to define best practices is ongoing. We outline the strengths and weaknesses of common strategies for employing physical models in undergraduate biology courses and describe a novel strategy that we have developed to pair 3D-printed models with guided inquiry learning to create inclusive and interactive learning experiences. We further introduce the STEM BUILD website, a resource that we have developed to facilitate collaboration among instructors, makers, researchers, and Universal Design for Learning experts and reduce barriers to broad implementation of inclusive kinesthetic learning activities.

INTRODUCTION

Modern biology has been transformed by the ability to see cells and molecules in increasing detail. However, as scientific understanding of three-dimensional (3D) structures, processes, and interactions has increased, instructors' tools for teaching biology in 3D have lagged. Traditional representations of visual information not only fail to accurately depict 3D biology, they fail to include students with disabilities that affect their vision or visual processing. The emergence of 3D printing labs termed “makerspaces” on college and university campuses has facilitated a surge in courses incorporating 3D-printed models (1). While both 3D-printed and “homemade” kinesthetic models enhance student learning in multiple settings (2–10), developing models paired with lessons that not only allow learners to build their understanding but include all learners requires expertise in Universal Design for Learning (UDL), constructivist pedagogies, and 3D design and printing.

Universal design for learning refers to the practice of creating opportunities for multiple means of engagement, representation, and expression (11–14). It acknowledges that regardless of ability, individuals learn differently, and that presenting information in multiple ways and allowing students multiple ways of demonstrating their learning allows

all students the opportunity to succeed. Universal design for learning stands in contrast to the standard accommodation-based model for teaching students with disabilities. Rather than designing a course with able students in mind and retroactively creating accommodations for students with disabilities, an instructor using UDL intentionally creates learning materials and assessments that are accessible to all students, making accommodations less necessary.

Constructivist pedagogies are based on the theory of Jean Piaget that knowledge cannot be transferred, but, rather, an individual must create that knowledge by connecting new concepts to concepts that they have already learned (15, 16). This idea that knowledge must be built by the learner is implicit in all active-learning strategies and is explicitly targeted by multiple impactful pedagogical techniques used in STEM disciplines, including Problem-Based Learning (PBL), Peer-Led Team Learning (PLTL), and Process-Oriented Guided Inquiry Learning (POGIL) (16, 17).

These two ideas—that instructors should include all learners by creating opportunities for multiple means of representation and that constructivist pedagogies benefit all students—provide a framework for inclusive STEM learning activities that can be applied to the ways in which students learn about 3D structures and processes in biology. The use of hands-on models improves student understanding of 3D biological concepts, from molecular interactions to embryonic development (10, 18–20). However, until recently, the use of tactile methods of teaching visual concepts has been limited by availability of materials. Cellular and molecular models have typically been purchased from educational suppliers; thus, instructors who wished to develop activities using models that were not commercially available had to build models themselves using arts-and-crafts supplies.

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While this approach has merit, hand-building models is time-intensive for instructors and often does not result in scientifically accurate representations.

As the proliferation of makerspaces drives increased incorporation of 3D-printed models into biology courses, it is critical to define a set of best practices that ensures these models are used in ways that 1) result in active, effortful (and productive) learning, and 2) include all learners. In an effort to begin defining these best practices, we review existing frameworks for incorporation of 3D models; describe a novel strategy we have developed to design, implement, and assess impactful 3D model-based learning experiences; and introduce the STEM BUILD website, an online community developed to decrease barriers to broad implementation and assessment of these activities.

APPROACHES TO INCORPORATING 3D MODELS IN THE CLASSROOM

Structure-focused strategies

The majority of the published studies of 3D models in the classroom focus on structure (4, 5, 7, 18, 21). The ways in which these models are incorporated into the class fall into three categories: instructor-led demonstrations, in-class activities, and student-driven 3D printing projects (Table 1).

Instructor-led demonstrations. The simplest method of incorporating 3D-printed models in the classroom is to create one or a few models of a molecule or cell that can be used by the instructor to supplement two-dimensional (2D) representations. The creation of these models is often as simple as converting a structure from a Protein Data Base (PDB) file to an appropriate format for 3D printing using tools available from the NIH 3D Print Exchange (<https://3dprint.nih.gov/create>) (22). This approach improves upon demonstrations using commercially available models by allowing the instructor to present any molecule for which a structure has been published rather than limiting their selection to those chosen for production by a company. Moreover, instructors with access to a 3D printer can create a simple model for less than \$1 (e.g., a single amino acid intended to practice formation of peptide bonds [<https://stembuild.ncsu.edu/resource/amino-acid-models-with-braille-v1/>] costs 25 cents to print), and even more complex molecular structures printed using a university 3D printing service with more advanced materials cost in the range of \$20 to \$50. In contrast, commercial models can cost up to \$500 or more (<https://www.3dmoleculardesigns.com/Education-Products/CRISPR-Cas9-Mini-Model.htm>). Using these models in the classroom is a significant improvement over only providing standard visual representations. Moreover, if the students can hold the models, this method enables blind and visually impaired students to perceive information that they would not be able to access through standard visual representations. However, simply using models as a

replacement for 2D images still represents a passive learning strategy, in which students see, and potentially feel, the model but do not interact with the model, each other, or the instructor to create their own understanding.

In-class activities. With increased access to 3D printing, it is feasible for instructors to print a class set of 3D models and design accompanying classroom activities that promote active learning (1). Studies of interactive model-based activities used to teach topics related to molecular structure have demonstrated both learning gains and increased student engagement (4, 5, 7). Moreover, access to 3D-printed models improved students' ability to answer higher-order questions about molecular structures in an oral interview setting (18). However, it is important to design the activity in a way that guides all students to find the relevant facets of the structure.

Student-driven 3D printing projects. In another strategy, students are asked to choose a cell or molecule of interest and create their own 3D model (21). These projects may span a few weeks or an entire semester and may require students to complete research and written work in addition to creating the model. Thus, students gain a deep understanding of their chosen molecule or cell but focus only on the structure they selected to study (21). If well designed, this is a useful strategy for students to learn basic concepts about structure that could then be applied to other structures they may later encounter.

Function-focused strategies

Studies of these strategies provide evidence that 3D models are effective for teaching concepts related to molecular structure (4, 5, 7, 18, 21). When the goal of the model is to teach function, however, additional strategies are necessary, as the focus is not solely on the model, but on developing active-learning classroom activities in which the model can be used.

Interactive kinesthetic classroom activities. A fourth strategy uses models to teach concepts related to molecular interactions or cellular processes that occur in three dimensions, and the learning outcomes are centered on the steps of the process. With these goals, 3D models that precisely depict molecular structure are less important than crafting a classroom experience that allows students to interact with the individual components to construct their understanding of the pathway or process.

Kinesthetic activities in which models are created using craft supplies have been used to teach topics such as the central dogma of molecular biology, cell division, and cellular respiration (3, 23, 24). Other studies have incorporated 3D-printed models borrowed from lending libraries (25). In these activities, students are walked through the steps needed to simulate the biological process with the model. Because these activities emphasize listing or explaining steps of biological processes, they are best used for learning outcomes associated with lower levels of Bloom's taxonomy.

TABLE I.
Strategies for teaching with physical models.

Strategy	Best for	Strengths	Weaknesses
Instructor-led demonstration	Molecular or cellular structures	<ul style="list-style-type: none"> • Allows 3D visualization of structures • Less instructor time required than other strategies • Less classroom time required than other strategies • Feasible to use for numerous structures 	<ul style="list-style-type: none"> • Passive learning • Does not include students with visual disabilities
Student-driven 3D printing projects	Molecular or cellular structures	<ul style="list-style-type: none"> • Students engage deeply with one structure 	<ul style="list-style-type: none"> • Students only learn about one or a few structures • Does not include students with visual disabilities
Structure-focused in-class activities	Molecular or cellular structures	<ul style="list-style-type: none"> • Allows 3D visualization of structures • Active learning • Some models can be purchased or borrowed from third parties 	<ul style="list-style-type: none"> • Requires more instructor time than other structure-based strategies • Requires more classroom time than other structure-based strategies
Interactive kinesthetic classroom activity	Biological processes or interactions	<ul style="list-style-type: none"> • Active learning • Models do not require special skills to create 	<ul style="list-style-type: none"> • Focus on lower-level learning outcomes • Many models do not include students with visual disabilities
Tactile Teaching Tools with guided inquiry	Biological processes or interactions	<ul style="list-style-type: none"> • Active learning • Uses constructivist pedagogy • Allows experimentation with models • Can address higher-level learning outcomes • Incorporates UDL 	<ul style="list-style-type: none"> • Large amount of instructor time • Large amount of class time • Requires UDL knowledge • Some models require additional electronics to engage senses other than vision

UDL = Universal Design for Learning.

Furthermore, in most cases, these activities are not accessible to students with disabilities affecting their vision or hearing.

Tactile teaching tools: constructivist 3D biology puzzles. The ability to use 3D printing to create interactive molecular puzzles has expanded the types of learning outcomes that can be addressed with kinesthetic classroom activities to include prediction of outcomes when the system is perturbed. We have taken advantage of 3D printing technologies to develop 3D puzzles paired with Process-Oriented Guided Inquiry Learning (POGIL)-based classroom activities (26–28), termed Tactile Teaching Tools (TTTs). This pairing takes advantage of the constructivist base of POGIL while shifting from 2D to 3D representations, engaging multiple sensory inputs, and including students with sensory disabilities.

In this strategy, design of the TTT itself and the paired Guided Inquiry Learning (GIL) activity are of equal importance. Similar to POGIL activities, TTT-GIL activities begin with simple exercises in which students identify the parts of the model. They then progressively add layers of complexity as they work in groups to explore how the pieces of the puzzle interact. These TTTs range from simple 3D models used to practice bond formation to advanced multi-part puzzles containing magnets, electronics, lights, and motors. For example, we have developed an interactive

3D *lac* operon puzzle (29). For the activity paired with this TTT, students first complete an existing POGIL exercise related to transcription and translation (30, 31) and then use the puzzle to answer questions related to higher-order learning outcomes. Unlike traditional methods of teaching these concepts, or even the existing POGIL activity, the *lac* operon puzzle is accessible to blind and visually disabled students: the pieces of the puzzle can be identified through tactile interactions, and transcriptional activation is simulated by vibration.

In addition to the ability to create custom molecular interaction puzzles, 3D printing makes it possible to incorporate UDL in the design process (11). TTTs can be designed with multiple means of representation; for example, an output can be simulated by a light, a sound, a vibration, or all three. More basic TTTs can be designed so that information that is represented by different colors is also represented by different textures. Moreover, online Braille translators such as touchsee.me convert any text into a 3D-printable STL file in Braille, allowing written information (e.g., nucleotide or amino acid abbreviations) to be added to the model in Braille (<https://stembuild.ncsu.edu/resource/amino-acid-models-with-braille-v1/>). By making these models inclusive by design, we aim to enhance the learning experience for all students.

Barriers to implementation of TTTs

While Tactile Teaching Tools (TTTs) provide a method of using 3D models in a constructivist and inclusive manner, several barriers currently limit their broad implementation:

1. **Access to technology.** Although makerspaces are becoming more common, smaller institutions are less likely to have them. In some cases, access to 3D printers may exist without staff to provide training and advice to interested instructors, or without access to other technologies necessary to craft TTTs that require electronics.
2. **Instructor time.** Developing, prototyping, and mass printing classroom sets of TTTs, particularly for large enrollment courses, is an extremely time-intensive undertaking.
3. **Cost.** The plastic filament used for 3D printing is inexpensive, and 3D-printed models are generally much more cost effective than commercially available models. However, models requiring electronics are more expensive to create.
4. **Technical skills.** To create TTTs, an instructor needs to know not just how to operate a 3D printer but also how to use design software to create the print file, and potentially how to wire and solder.
5. **Pedagogical training.** If the goal of TTTs is to facilitate constructivist learning of three-dimensional concepts and processes in a way that includes all students, instructors need to be trained in constructivist pedagogies such as Process-Oriented Guided Inquiry Learning (POGIL) as well as Universal Design for Learning (UDL).
6. **Classroom time.** Effective implementation of TTTs requires devoting more class time to a topic than does teaching it using traditional methods. Thus, this strategy should only be used for concepts that cannot be taught effectively through other means.
7. **Credit.** Considering the time and effort required to successfully develop and implement TTTs, instructors may be concerned about receiving credit for their efforts in a way that can be included in a CV or promotion and tenure dossier. Some instructors may choose to assess the effectiveness of their TTTs and publish their findings in a peer-reviewed journal. However, more instructors might be willing to develop TTT-GIL activities if there were a mechanism for receiving credit that did not require peer-reviewed publication.
8. **Sharing.** In many cases, a model for a given concept or process may exist but remain unpublished. While sites for sharing 3D print files (e.g., Thingiverse) and sites for sharing classroom-tested lessons (e.g., CourseSource) exist, there is currently no way to share models paired with lessons or to “mix and match” an existing model and a new lesson or vice-versa.

Activating collaboration

As we began to implement and assess TTTs in our courses, we recognized that the barriers we had identified meant that it was unlikely that any one individual would have all of the skills, resources, and time necessary. Thus, successful development and use of TTTs requires multiple collaborations.

THE STEM BUILD TEAM

To create our TTTs and activities, we assembled a core research team (STEM BUILD: **B**uilding **U**nderstanding through **I**nclusive **L**earning **D**esign) consisting of two faculty members and three undergraduate research assistants (URAs) funded by small internal grants. The URAs underwent basic 3D printing training at our institution’s makerspace. They then worked with us to conceptualize new TTTs and consulted with the makerspace professional staff for technical assistance during the design and prototyping phases. The URAs have been a critical part of our research team, as they provide a student perspective during the design and testing phases, and they have flexible schedules that allow them to start and pick up prints in the makerspace between classes. They benefit from participation by gaining transferrable design and prototyping skills, experience in study design and data analysis, opportunities to present their work at local and regional conferences, and co-authorship on peer-reviewed publications. Because creating paid undergraduate research positions is critical to building a diverse pipeline for STEM professionals, all of our URAs receive a salary, paid by internal grants, work study, or our institution’s Provost’s Professional Experience Program.

STEM BUILD WORKSHOP

To expand the use of TTTs outside of our classrooms, we sought out mechanisms to facilitate collaborations that would allow instructors interested in teaching with TTTs but lacking the necessary time, skills, and/or funds to bring their ideas to fruition. We began by organizing a workshop in which five NCSU faculty received training in 3D design and printing, GIL, UDL, and assessment. The faculty were each paired with one of the STEM BUILD URAs to continue prototyping and refining their models over the summer. Makerspace staff lent their technical expertise and advice on available maker technologies to help faculty explore design approaches. Because conceiving TTTs through a UDL lens is critical to the development of inclusive learning activities, we collaborated with an expert in accessibility to provide foundational education to faculty participants about the goals of UDL, and how to begin moving away from accommodation-based approaches to disabilities.

The TTTs developed by faculty participants varied in complexity from 3D prints of published molecular structures to multi-part systems with electronics and lights, and the production scale varied from a class of 16 to a class with three sections of 120 students. In total, four TTTs were developed as a result of this workshop, impacting over 500 students. Three of these TTT-GIL activities have been assessed in the classroom, and analysis of the results of these assessments is ongoing.

STEM BUILD WEBSITE

While the workshop facilitated implementation of TTTs for a small number of NCSU faculty by addressing barriers 1 through 5, the limitations of the workshop model are an inability to reach a large number of faculty at multiple institutions and failure to address issues surrounding sharing of TTT-GIL activities and assigning credit. To foster sharing and collaboration and to incentivize the development of new TTTs by providing a mechanism to receive credit, we worked with NCSU's Distance Education and Learning Technology Applications (DELTA) to create a website (<https://stembuild.ncsu.edu>) that serves as a central hub for dissemination of TTT print files, assembly instructions, and GIL activities. While the site is hosted by NCSU, users from other institutions and unaffiliated users can both access posted content and create accounts to upload models and lessons. Key features that differentiate this website from existing peer-reviewed journals and sites such as Thingiverse are summarized below.

1. **Has a low barrier to entry.** Although most TTT packages shared on the STEM BUILD website are classroom tested, no assessment data are required, and the website permits sharing of untested models or lesson plans. This allows an individual with an idea and expertise in lesson design but not 3D printing, for example, to share a lesson in need of a model and potentially find a collaborator to help with the design and prototyping process. Moreover, this allows instructors to find collaborators interested in assessing their models and lessons at different institutions and with different student populations. By facilitating collaboration, the STEM BUILD website could ultimately result in more robust studies of TTT-GIL activities than a single instructor could perform on their own. Thus, the STEM BUILD website provides a starting point for later peer-reviewed studies, which can then be linked to the model and lesson files housed on the website.
2. **Serves multiple communities.** The goal of the STEM BUILD website is to provide resources that activate collaborations among instructors, makers, educational researchers, and students. Each of these communities has unique expertise, and each community can make unique contributions to the website. For example, the STEM BUILD website allows sharing of a model developed by a student or maker without an associated lesson plan, or sharing of a lesson plan by an instructor without the associated model.
3. **Encourages multiple types of collaboration.** The STEM BUILD website is structured to encourage collaboration among individuals with different expertise and skillsets as well as instructors teaching similar concepts at different institutions or to different student populations. By creating a site for sharing TTTs and GIL lessons prior to classroom testing, the website encourages testing by multiple instructors in multiple settings. This could eventually result in multiple peer-reviewed publications focusing on different aspects of the TTT and its implementation, or collaboration on a larger study.
4. **Allows “re-mixing” of existing models and lessons.** Because each component of the TTT “package” can be shared independently, users of the website can “re-mix” models and lessons to create new classroom experiences. If an instructor finds a model that they would like to use in their class, but the existing lesson plan does not address their learning outcomes, the instructor can add an additional lesson plan that will also be associated with the model on the website.
5. **Allows quick publication of updates to models and lessons.** Models and lessons can be directly posted to the website without being subject to peer review, allowing authors to continually post updates to existing files as models are refined and lessons are tweaked for use in different courses. To prevent dissemination of inaccurate material, the website provides an ability to flag content for review if necessary. The STEM BUILD team regularly reviews posted content for scientific accuracy, and models or lessons that have been verified by the team receive a “BUILD VERIFIED” tag. When necessary, the team consults with external content experts.
6. **Provides a mechanism for credit.** Models and lessons shared on the STEM BUILD website can be cited and included on CVs. Furthermore, the website provides social media metrics to track “shares.”
7. **Provides an open access site for storage of lesson and model files with no publication costs.** To make sharing of TTTs and lessons accessible to as many stakeholders as possible, all files are freely accessible and there are no fees to share TTTs and/or lessons. This is particularly important considering that files can be submitted not just by faculty but also by students, makers, or any other interested individuals.

FUTURE GOALS

The advent of 3D printing technology has facilitated the development of new methods of teaching, and studies defining best practices for using 3D models are still in early stages. It is clear, however, that the ability to accurately represent 3D structures, interactions, and processes will continue to contribute to inclusive teaching in biology. As new technologies, such as virtual and augmented reality, begin to be adopted in the biology classroom, the STEM BUILD website will provide the infrastructure to connect technical experts, instructors, and UDL experts and facilitate collaborative efforts to define impactful and inclusive methods for incorporating novel teaching tools in the undergraduate biology classroom.

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