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Anatomy of STEM Teaching in American Universities: A Snapshot from a Large-Scale Observation Study

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Abstract

National and local initiatives focused on the transformation of STEM teaching in higher education have multiplied over the last decade. These initiatives often focus on measuring change in instructional practices, but it is difficult to monitor such change without a national picture of STEM educational practices, especially as characterized by common observational instruments. We characterized a snapshot of this landscape by conducting the first large scale observation-based study. We found that lecturing was prominent throughout the undergraduate STEM curriculum, even in classrooms with infrastructure designed to support active learning, indicating that further work is required to reform STEM education. Additionally, we established that STEM faculty’s instructional practices can vary substantially within a course, invalidating the commonly-used teaching evaluations based on a one-time observation.

One Sentence Summary:

Although lecture is prominent throughout the undergraduate STEM curriculum, STEM faculty employ varied teaching practices within the same course.

A large body of evidence unequivocally demonstrates that engaging students in the learning process through student-centered strategies (i.e., strategies that promote student interactions and cognitively engage students with content such as Peer Instruction (1)) (2, 3) leads to increased learning and affective gains for all students enrolled in Science, Technology, Engineering, and Mathematics (STEM) courses (4). Consequently, over the last ten years, the highest levels of American educational (2, 3) and governmental (5) bodies have called for and supported the widespread adoption of these strategies throughout the undergraduate STEM curriculum. To date, the national picture of the STEM instructional landscape has mostly been provided through national self-report surveys of faculty members within a particular STEM discipline (6–12); an exception includes a study of geoscience instructors (13), which implemented both surveys and classroom observations. Although self-report survey data can correlate well with observation data (13, 14), they are prone to reliability threats depending on the context in which the survey responses are collected (15). Moreover, few surveys implemented nationally to date provide valid and reliable data (16). Finally, survey data can underestimate the complexity of classroom environments whereas observational data can afford greater detail (17). The Classroom Observation Protocol for Undergraduate STEM (COPUS) (18) has rapidly become a favored instrument among STEM disciplines to provide more consistent assessment of instructional practices, as well as to document the impacts of educational initiatives (17, 19–24). We report here an unprecedented step toward a national characterization of STEM teaching practices by presenting the results of analyses of COPUS data collected from over 2,000 classes taught by more than 500 STEM faculty members across multiple institutions.

This large-scale data set enables distinctive contributions to current understanding of instructional practices in STEM courses. First, it allows for generalizations beyond institutional descriptions (17, 21, 22). Second, it suggests a resolution to inconsistent findings from recent discipline-based education research (DBER) studies. For example, STEM faculty report that it is more difficult to use student-centered techniques in large classrooms or less amenable physical layouts (25, 26), but previous studies have not borne this out in practice (21). Previous studies have also reported inconsistent relationships between course level (introductory or upper-division) and instructional practices (13, 19, 21). Third, classroom observations are often used for evaluative (i.e., promotion and tenure) purposes, as well as in research to document the impact of educational initiatives. More data is needed to guide such use of observational protocols to collect data in a valid way; for example, previous research suggests that at least three observations are needed for an accurate picture of instructional practices (21). Data collected for this report allows us to test the generalizability of all these findings by increasing the sample size of observations collected 7.5-fold over the Lund et. al. study. Finally, it addresses the call made in a recent report from the National Academies of Sciences, Engineering, and Medicine for new data collection to understand the use of evidence-based practices (27).

We used COPUS (18) to characterize 2,008 STEM classes taught by 548[1] individual faculty members. COPUS requires documenting the co-occurrence of 13 student behaviors (*e.g.* listening, answering questions) and 12 instructor behaviors (*e.g.* lecturing, posing questions) during each 2-minute interval of a class. This instrument, which was adapted from the Teaching Dimensions Observation Protocol (28), was selected for this study as it is broadly

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[1] Data came from an online tool that enables researchers to have their COPUS data analyzed - http://www.copusprofiles.org. Data entries did not always make it clear if the course was taught by the same instructor or at the same institution. These numbers thus represent minima.

used and has been empirically demonstrated to provide valid characterization of instructional practices in STEM classrooms (see Supplementary Materials) (17, 18, 20, 21, 24, 29, 30). Moreover, the high level of interrater reliability consistently achieved across studies employing COPUS ensures that the instrument can provide a reliable and valid characterization of STEM instructional practices on a large scale. Data came from 24[1] doctorate-granting universities and one primarily undergraduate institution, with the largest contributing institution comprising 17.1% of the data. Faculty were observed on average 2.7 times. 98.4% of the faculty were observed within the same semester and course. Details about instructors and courses observed are presented in Table 1.

Analyses of instructors' and students' behaviors revealed that instructors demonstrated a greater variety of behaviors (an average of six behaviors occurred in 10% or more of two-min intervals within a given class) compared to students (an average of three behaviors). Specifically, the most common instructor behaviors observed were lecture (an average of 74.9 ± 27.8% of the total two-min intervals of a given class), writing in real time (35.0 ± 35.2%), posing non-rhetorical questions (25.0 ± 21.4%), following-up on questions (14.3 ± 18.9%), answering student questions (11.5 ± 12.8%), and administering clicker questions (10.0 ± 16.5%). Students primarily listened to the instructor (87.1 ± 20.8%), answered instructor questions (21.6 ± 19.8%), and asked questions (10.4 ± 12.1%). Complete distributions for all instructor and student behaviors can be found in the supplemental information.

Simply describing instructor and student behaviors across our sample leaves out pertinent information regarding the characterization of instructional practices in STEM undergraduate courses. Knowing that lecture is prevalent does not accurately reflect what other strategies are being implemented alongside or instead of lecture. To answer this question, we conducted latent profile analysis (LPA) on eight of the instructor and student behaviors. More details about LPA and how we chose a final solution are available in the supplemental information (31–38). We created clusters based on four instructor behaviors (lecture, posing questions, clicker questions, and one-on-one work with students) and four student behaviors (group work on clicker questions, group work on worksheets, other group work, and asking questions). We chose these eight behaviors because they were observed with adequate heterogeneity, were not highly correlated with each other, and were likely to be key strategies in active or non-active learning environments. The solution consisted of seven clusters, each representing a unique instructional profile (Fig. 1).

The first group of instructional profiles, clusters 1 and 2, depicts classrooms in which 80% or more of class time consists of lecturing. Cluster 1 has no observed student involvement except sporadic questions from and to the students, while Cluster 2 has clicker questions that are sometimes associated with group work. We labeled this group of profiles "Didactic" instructional style; 55% of the observations collected belonged to this broad instructional style. The second group of profiles, which we named "Interactive Lecture," consists of Cluster 3 and Cluster 4. These clusters represent instructors who supplement lecture with more student-centered strategies such as *Other group activities* (Cluster 3) and *Clicker questions with group work* (Cluster 4); 27% of the observations were classified in this instructional style. Finally, clusters 5, 6, and 7 depict instructors who incorporate student-centered strategies into large portions of their classes. Cluster 5 represents a variety of group work strategies consistently used, while Cluster 7 represents a similar variety, but with less consistent usage. Some in Cluster 6 may resemble a popular style of instruction called POGIL, Process Oriented Guided Inquiry Learning (39), but others (due to a higher proportion of lecture) likely represent other strategies that incorporate group worksheets and one-on-one assistance from the instructor. We labeled this third group of clusters "Student-Centered" instructional style. This instructional style represents almost a fifth of the data set. Our results offer a succinct, yet comprehensive, classification of instructional practices observed across STEM courses. Given the sample size and diversity of courses and disciplines represented, we are confident that the profiles and broad instructional styles provide a reliable picture of the current instructional landscape in undergraduate STEM courses taught at doctorate-granting institutions.

We leveraged the identification of the three broad instructional styles to test our hypotheses and address discrepancies among prior DBER studies (Fig. 2). We report the results of Chi square analyses below and only claim statistical relationships when differences led to standard residuals greater than three (40); no statistically significant interaction effects were observed. Our first hypothesis – instructors of smaller courses or in classrooms with flexible physical layout would implement more student-centered strategies while instructors of larger courses or in classrooms with fixed physical layout would tend to use traditional lecture styles – was supported.

Observations in large courses were classified in the didactic instructional style more than expected by random chance and in the student-centered instructional style less than expected by chance, while the opposite occurred for small courses, χ^2 (4, $N = 1753$) = 56.5, $p < 0.001$, $V = 0.13$. Classrooms with flexible seating were more likely to be classified in the student-centered instructional style, χ^2 (2, $N = 1137$) = 55.9, $p < 0.001$, $V = 0.22$. Interestingly, about half of the classes with flexible seating and about half of the small and medium courses were classified as didactic style of instruction. This result implies that simply providing adequate infrastructure or small class size does not necessarily change instructional practices. Second, we found no significant relationships between instructional style and course level, suggesting that instructional style is similar throughout the curriculum, χ^2 (8, $N = 1927$) = 11.0, $p = 0.20$. This outcome confirms the findings from other studies (13, 19). We were also interested in differences by discipline since the affordances of content, disciplinary teaching conventions, and educational research traditions are different for each. However, the relative proportions are skewed by more chemistry and biology classes in the data, so we only made statistical inferences about these disciplines. The results (Fig. 2D) indicate that chemistry classes tended to be classified in the didactic style while biology classes were relatively more frequently associated with the student-centered instructional style, χ^2 (2, $N = 1328$) = 36.5, $p < 0.001$, $V = 0.17$.

Finally, we explored the diversity of instructional styles implemented by STEM instructors in order to estimate the minimum number of observations required to accurately depict their instructional practice. As in previous research (21), we found that individual instructors vary their teaching from day to day. Among the instructors who were observed multiple times, approximately half (53.3%) had their classes classified into one of the three broad instructional styles, 41.1% had their classes classified in two styles, and 5.6% into all three styles. The more frequently an instructor was observed, the greater the number of broad instructional styles under which her/his teaching was classified (Fig. 2F). Figure 2e highlights that the proportion of interactive lecture and student-centered instructional style increase with the number of observations per faculty. Our data thus suggest that faculty do not employ the same style throughout a semester and that at least four observations are necessary for reliable characterization of their teaching.

In conclusion,

1. This report confirms anecdotal accounts that didactic practices (i.e., lecturing and other teacher-centered behaviors) are prevalent throughout the undergraduate STEM curriculum despite ample evidence to the limited impact of these practices and significant interest on the part of institutions and national organizations in education reform. The scale from which the findings are derived indicates the pervasiveness of didactic teaching in STEM higher education. This result should prompt institutions and STEM disciplines to reflect on practices and policies that sustain this status quo and identify systemic reform strategies;
2. This report provides a unique baseline of data for comparison for educational initiatives determining the impact of their intervention, for professional development facilitators to inform the design of their programs, and for faculty when they receive COPUS data. The seven instructional profiles allow these comparisons to move beyond the binary teacher- or student-centered teaching classification and to inform incremental and diverse paths toward student-centered teaching;
3. This report challenges survey-based studies in which faculty identify classroom layouts and course size as barriers to instructional innovation. The results show that flexible classroom layouts and small course sizes do not necessarily lead to an increase in student-centered practices. Investments in pedagogical training for users of these environments is thus critical in order for the expenditure on infrastructure to be impactful;
4. This report confirms findings from prior small-scale studies that STEM faculty are complex instructors, who often use a variety of instructional strategies within the same course. Therefore, reliable characterization of instructional practices requires at least four visits. This new finding challenges current practices in promotion and tenure evaluation of faculty’s teaching, which often include peer observation of just one class in an academic year.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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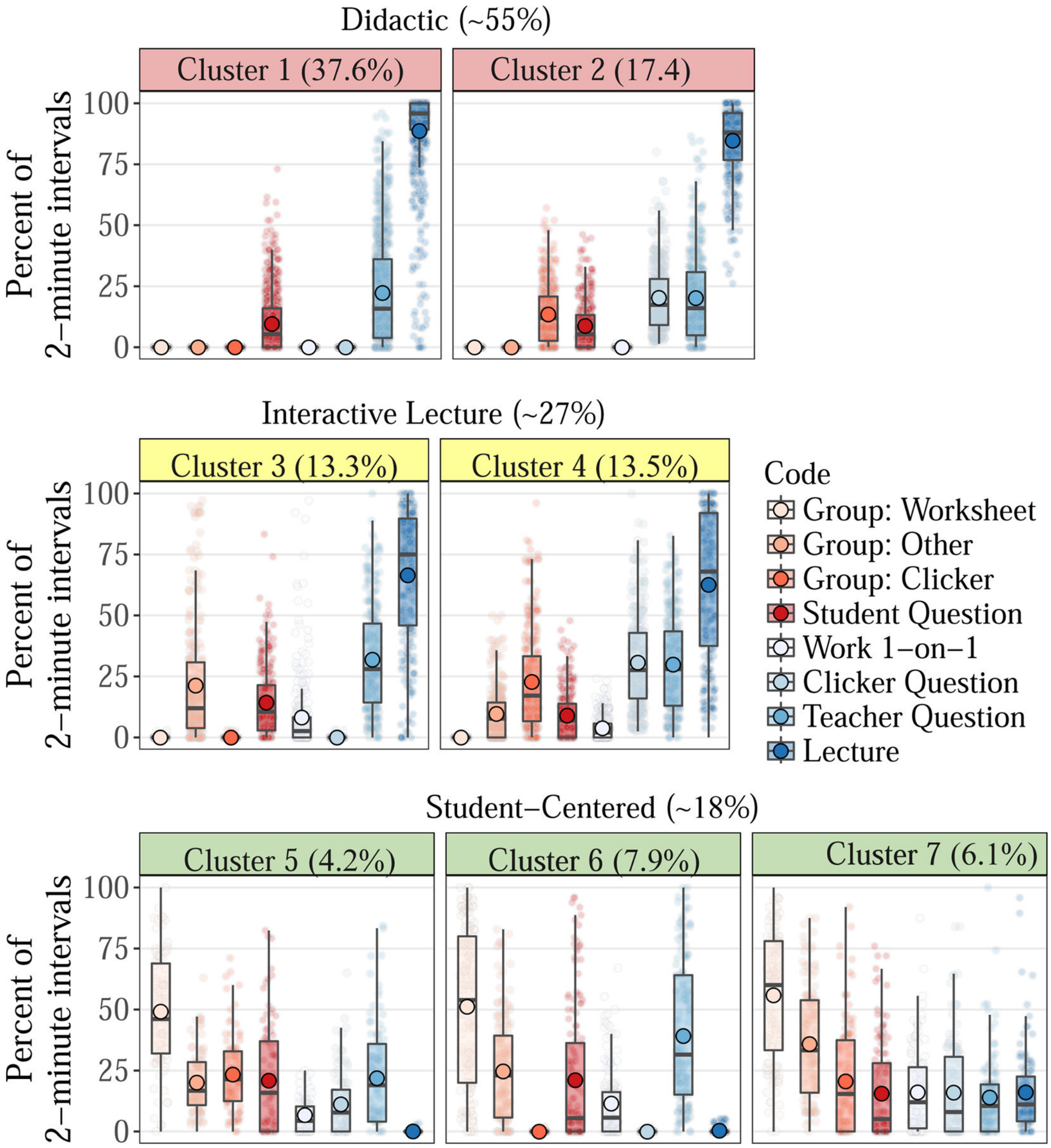

Fig. 1.

Broad instructional styles and their associated instructional profiles. Each panel shows a single cluster (profile) along with the percent of observations that were classified in that cluster. Each panel shows the average (solid circle), boxplot (hollow, grey outline), and individual data points (faint points) for each of the students (reds) and instructor behaviors (blues).

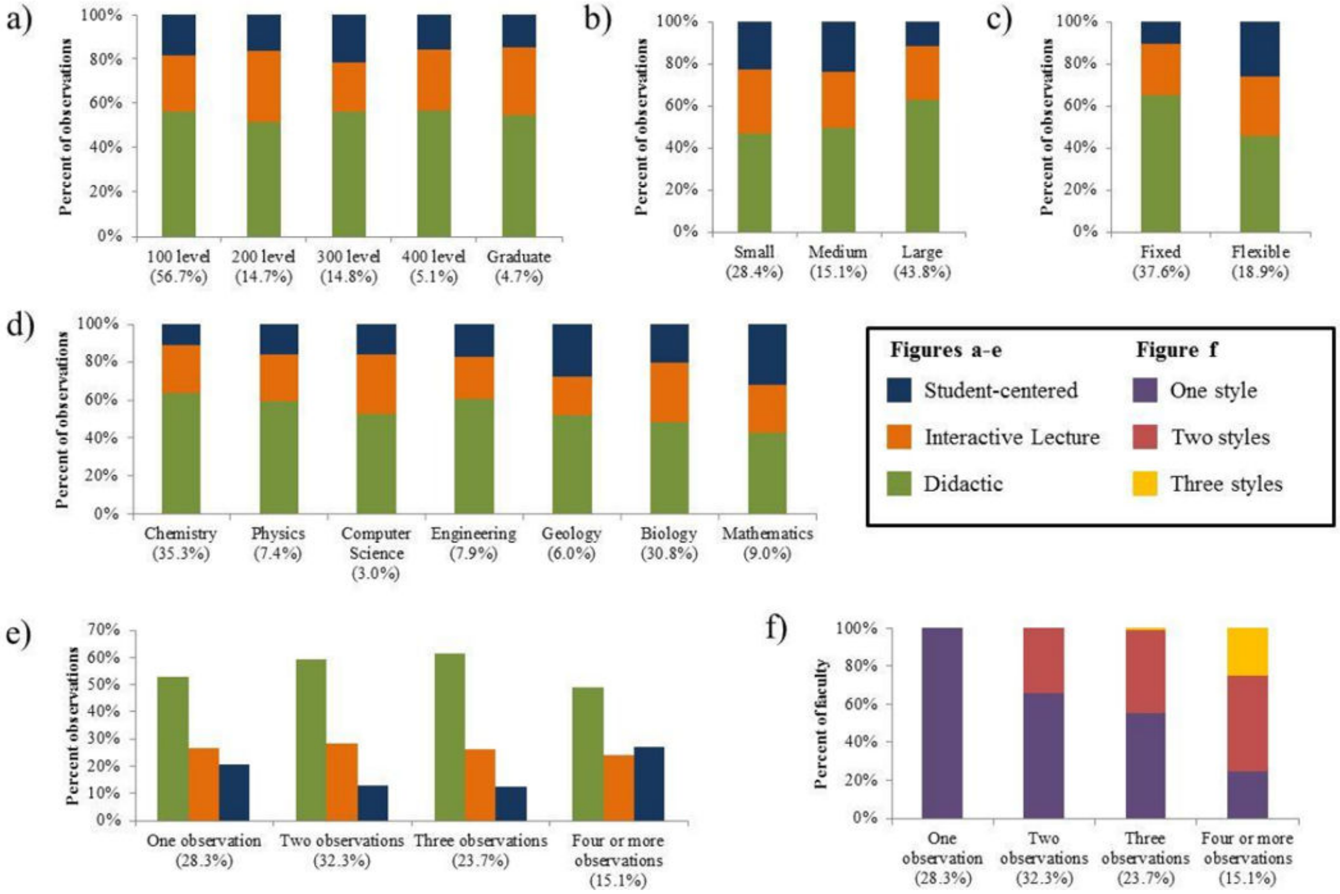

Fig. 2.

Distribution of the three broad instructional styles across A) course level, B) course size, C) classroom physical layout, D) STEM discipline, E) number of observations per faculty; F) represents the relationship between frequency of observations and classification of observations in one, two, and all three broad instructional styles.

Table 1.

Study sample

Demographic		Classroom observations		Instructors	
		Frequency	**Percent**	**Frequency**	**Percent**
Discipline	Biology	619	30.8	179	31.6
	Chemistry	709	35.3	122	21.5
	Computer Science	61	3.0	21	3.7
	Engineering	159	7.9	78	13.8
	Geology	121	6.0	36	6.3
	Mathematics	177	8.8	56	9.9
	Physics	148	7.4	66	11.6
	Missing data	14	0.7	9	1.6
Course level	100 level	1,140	56.8	249	43.8
	200 level	294	14.6	85	15.0
	300 level	296	14.7	110	19.4
	400 level	102	5.1	39	6.9
	Graduate	95	4.7	34	6.0
	Missing data	74	3.7	44	7.7
Course Size	Small (0–50)	570	28.4	167	29.5
	Medium (51–100)	302	15.0	80	14.1
	Large (>101)	881	43.9	158	27.9
	Missing data	255	12.7	162	28.6
Classroom Layout	Fixed	757	37.7	120	21.5
	Flexible	380	18.8	87	15.7
	Missing data	871	43.4	350	62.8