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Applying Insights from Faculty Teaching Practices to Science and Math Education Reforms

By Matthew Tadashi Hora

KEY POINTS

1. Teaching practices vary considerably by discipline, so "STEM" as a catch-all category may not make sense in practice. Instead, policymakers and practitioners should focus on discipline-specific practices and workplace conditions when considering pedagogical reforms.
2. Pedagogical reform efforts must be grounded in more detailed accounts of teaching practice, which can provide insights into the nature of educational reform, implicate new ways to think about program design, identify leverage points for future interventions, and contribute to program evaluation and institutional assessments.

ABOUT THE AUTHOR

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Introduction

Policymakers and educators are increasingly expressing concerns that the U.S. is lagging behind other countries—notably China and India—in educating the next generation of mathematicians and scientists who will create the products and innovations that drive the 21st century economy. In addition, concerns about the underrepresentation of women and minorities in science and math contribute to a rising chorus of critiques of how these disciplines are taught in *institutions of higher education* (IHEs).

> ...many IHEs are encouraging STEM instructors to adopt interactive, inquiry-based teaching methods in their classes, laboratories, and discussion sections.

In response, the federal government, private foundations, and many IHEs are encouraging STEM (science, technology, engineering, and math) instructors to adopt interactive, inquiry-based teaching methods in their classes, laboratories, and discussion sections. For example, the Nobel-prize winning physicist Carl Weiman recently developed a five-year $15 million initiative called the Science Education Initiative (SEI) at the University of British Columbia and the University of Colorado at Boulder to help math and science faculty develop research-based learning goals and corresponding teaching and assessment strategies.

Many of the strategies for changing teaching practices are based on research from the learning sciences that links improved student learning and the acquisition of higher order cognitive skills with methods such as problem-based learning, as opposed to a singular reliance on traditional, didactic lecturing.[1]

Research also suggests that one of the reasons students drop out of math and science majors is the perceived poor quality of instruction and lack of opportunities to be more actively engaged with their instructors and the material.[2] Based on this evidence, efforts to encourage instructors to adopt research-based teaching methods are on the rise.

However, evidence also suggests that the adoption of interactive teaching techniques is slow. Research on the diffusion of innovations reveals that structural barriers, entrenched cultures, and top-down interventions that conflict with local practices can contribute to the maintenance of the status quo.

Furthermore, individual instructors play a key role in the organizational change process because they adopt, adapt, or reject new policies and innovations based on a combination of their own expectations and experiences, local traditions, and, especially, the multiple demands and pressures that shape classroom practice. Thus, a major challenge facing policymakers and educators engaged in pedagogical reform in math and science is to fully understand teaching practices in IHEs and how instructors experience their organizational environment in regards to their teaching responsibilities.

An adequate accounting of these complex phenomena involves capturing many different aspects of teaching practice. This includes

- moving beyond a narrow conception of teaching that is limited to providing lists of specific teaching methods (e.g., lecture and small-group discussion) utilized during a class;[3]
- accounting for the influence of contextual factors in the form of *artifacts* (designed entities such as curriculum or instructional technology);
- documenting aspects of teacher-student interactions, including the *cognitive demand* (instructors' expectations of the depth and complexity of student thinking) placed upon students throughout the course of a class; and
- understanding the course planning process wherein the instructor makes decisions about which topics to teach, and how, according to the *perceived constraints* (curricular pressures, time, etc.) that their department or IHE places on their teaching practice.

> ...structural barriers, entrenched cultures, and top-down interventions... contribute to the maintenance of the status quo.

Importantly, these facets of teaching do not exist in isolation from one another, but constitute parts of a larger *system-of-practice* wherein they interact synergistically in real-time.

However, current approaches to studying teaching practices are limited in their ability to capture these aspects by

- reliance on self-reported survey and interview data that lack validity;
- an overly reductive view of teaching as simply the specific teaching methods used by instructors;
- lack of observation protocols that account for multiple dimensions of teaching practice; and
- limited use of analytic techniques to discern the underlying patterns within observation data.

This brief presents an approach that addresses these limitations and captures the nuances of teaching practice with the specific aim of providing actionable evidence for policymakers and practitioners.

Methods

The Culture, Cognition, and Evaluation of STEM Higher Education Reform (CCHER) project is a National Science Foundation-funded, mixed-methods study focused on untangling the various influences and components of teaching practices in IHEs.[4] Our approach to analyzing teaching practices in real-time is based on *systems-of-practice theory*, which accounts for the synergistic interactions among actors, artifacts, and tasks that collectively constitute an entire *activity system*.[5] In this way, the unit of analysis is not the individual instructor, but their interactions with the tasks they engage in and the artifacts they use during a class.

A key part of the CCHER study included developing a new observation instrument that captures three dimensions of teaching practices (teaching techniques, cognitive demand, and instructional artifacts) called the Teaching Dimensions Observation Protocol (TDOP). The TDOP includes codes representing various teaching practices. In this study, analysts conducted observations every five minutes over the course of a 50- to 70-minute class period and circled TDOP codes corresponding to the practices they witnessed.[6] Thus, a 50-minute class yields 10 separate sets of data that could be populated with a variety of individual codes.

In the spring of 2010, researchers observed 57 instructors in five disciplines (mathematics, biology, physics, chemistry, and earth/space sciences) at three research IHEs, including the University of Wisconsin–Madison. Each instructor was interviewed once and

Table 1
Description of Study Sample

	CCHER Sample	
	n	%
Level of Course		
Lower division	39	68%
Upper division	18	32%
Sex		
Female	22	39%
Male	35	61%
Discipline		
Math	18	32%
Physics	11	19%
Chemistry	9	16%
Biology	11	19%
Earth/Space science	8	14%

	CCHER Sample		Spring 2010 Instructors	
	n	%	n	%
Position Type				
Lecturer	29	51%	140	53%
Assistant Professor	6	11%	24	9%
Associate Professor	4	7%	20	8%
Professor	18	31%	79	30%

observed twice for a total of 109 observed classes.[7] Information about the study sample is provided in Table 1.

The observation data were analyzed descriptively by identifying the percentage of total intervals in which a particular code was observed and through *network analysis* procedures, which depict the strength and extent of interactions among codes. The interview data were analyzed using *thematic analysis* procedures to identify perceived constraints to teaching.[8]

Findings

Results from Wave 1 of the CCHER study are reported in this brief for the entire sample (57 instructors; 109 classes) as well as for physics and math instructors in order to examine any disciplinary variations in teaching. Findings are grouped into three areas: 1) descriptive accounts of specific teaching practices, 2) inter-connections among teaching practices, and 3) perceived constraints on teaching.

Descriptive Accounts of Specific Teaching Practices

First, data from the classroom observations are presented for three teaching practices: 1) teaching methods, 2) cognitive demands, and 3) instructional artifacts. These data represent the percentage of total intervals in which a particular code was observed.

Teaching Methods

Table 2 depicts the percentage of intervals in which a particular teaching method was observed for given groups. The methods were identified through a review of the literature, a pilot study, and consultations with instructors in math and science fields.

Table 2

Percentage of Total Intervals in which Specific Teaching Methods Were Observed During Classes

	Entire Sample 1,178 intervals 57 classes	**Mathematics** 381 intervals 18 classes	**Physics** 219 intervals 11 classes
Teaching Methods			
Lecture	83%	75%	93%
Illustration	12%	7%	13%
Demonstration	10%	1%	40%
Small group discussion	3%	4%	4%
Whole class discussion	2%	0%	0%
Multimedia	3%	0%	7%
Case study	2%	0.1%	0%
Worked out problems	27%	66%	18%
Desk work	5%	10%	1%
Online techniques	0%	1%	0%
Brainstorm	1%	0%	1%
Rhetorical question	8.5%	11%	5%
Display conceptual question	22%	21%	17%
Display algorithmic question	9%	24%	3%
Comprehension question	13%	21%	5%
Novel question	6%	8%	3%
Clicker conceptual question	6%	0%	8%
Clicker algorithmic question	1%	0%	5%

The specific teaching methods observed for the entire sample indicate a strong reliance on the *lecture method* (83%). For secondary methods, instructors *worked out problems* (27%) and posed questions to students including *conceptual questions* (e.g., How does Coloumb's law relate to motion?) (22%), *algorithmic questions* (e.g., What is the solution for X?) (9%), and *comprehension questions* (e.g., Do you understand?) (13%).

For math and physics instructors, the lecture method also was prevalent, but with stark differences in relation to the use of working out problems, *demonstrations*, and different types of questions. It is also important to note that particular categories, such as the lecture method, were often used in conjunction with other methods (e.g., *illustration*, *rhetorical question*, etc.), which is apparent in the network analyses. This underscores the danger in interpreting teaching practices based on reported frequencies of single methods, as they frequently co-occur with other methods or change rapidly from moment to moment.

Cognitive Demands

Table 3 depicts the percentage of intervals in which a type of cognitive demand was observed. These data are based on analysts' interpretations of the types of thinking that instructors expected of their students. For example, the category *receive/ memorize* would be selected if an instructor presented facts, concepts, or ideas in a way that did not invite a student response or active engagement with the material.

The dominant cognitive demand observed for the entire sample was the receive/memorize category (89%), with the secondary type being *problem-solving* (31%), where students were expected to follow and understand the specific solution paths for solving problems.

Table 3
Percentage of Total Intervals in which Specific Cognitive Demands were Observed During Classes

	Entire Sample 1,178 intervals 57 classes	**Mathematics** 381 intervals 18 classes	**Physics** 219 intervals 11 classes
Cognitive Demands			
Receive/memorize	89%	83%	93%
Problem solving	31%	58%	28%
Creating	8%	6%	11%
Integration	7%	7%	7%
Connections to real world	14%	6%	24%

Table 4

Percentage of Total Intervals in which Specific Instructional Artifacts were Observed During Classes

	Entire Sample 1,178 intervals 57 classes	**Mathematics** 381 intervals 18 classes	**Physics** 219 intervals 11 classes
Artifacts			
Blackboard	41%	75%	48%
Laptop/slides	45%	0%	57%
Handouts	2%	0.1%	0%
Book	0%	1%	0%
Demonstration equipment	7%	0%	33%
Clickers (conceptual question)	6%	0%	8%
Clickers (algorithmic question)	1%	0%	5%
Miscellaneous object	6%	3%	11%
Pointer	19%	0%	9%
Digital tablet	5%	6%	9%
Poster	1%	0%	1%

The receive/memorize category was also dominant for math and physics instructors, with more emphasis in physics than mathematics, where many intervals were coded for problem solving. This is unsurprising since many math instructors were observed working out problems on the blackboards during the class. Additionally, physics instructors' frequent use of demonstrations and lectures interspersed with illustrations from the physical world was often accompanied by the *connections to the real world* cognitive demand.

Instructional Artifact Use

Table 4 depicts the percentage of intervals in which a type of artifact was observed. The primary artifacts observed for the entire sample include *laptop computers* (45%), which were used primarily to project PowerPoint slides, and *blackboards* (41%).

Secondary artifacts included *pointers* (19%), which were generally used to indicate key aspects of projected slides or solution paths to problems written on the board, and *clicker response systems* (6% with conceptual questions and 1% with algorithmic questions).

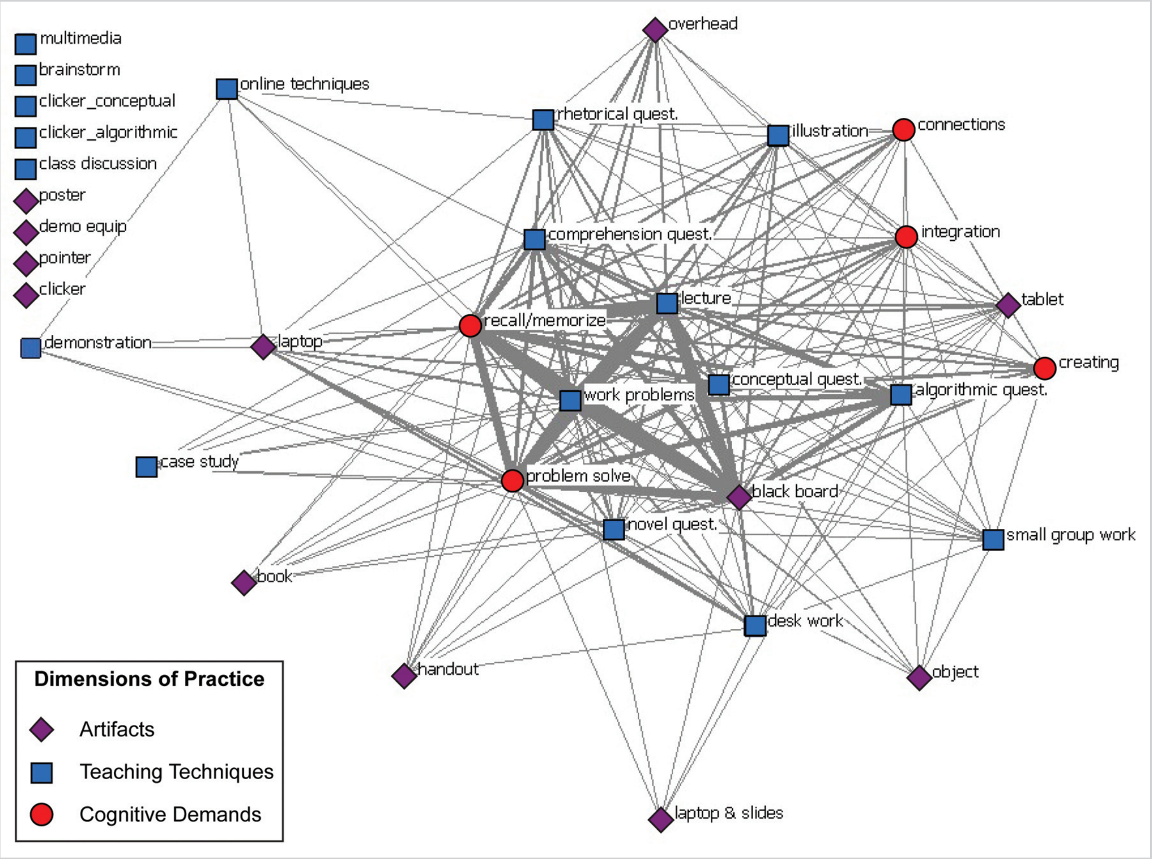
The data indicate differences between disciplines. Mathematics instructors primarily used blackboards while physics instructors split their artifact use among blackboards, laptop/slides, and *demonstration equipment*.

Inter-Connections Among Teaching Practices

While descriptions of specific teaching practices are revealing, they are only fruitfully interpreted as constituent parts of a synergistic whole, rather than isolated features of teaching practice. Systems-of-practice theory argues that teaching is a complex act involving the simultaneous interactions among these different features, and we analyzed these data using network analysis techniques in order to depict how they interact during a class period. The results include *affiliation network graphs* that illustrate the strength of the affiliation between two particular codes, as represented by the relative thickness of the lines.[9] We present affiliation network graphs for math and physics instructors separately. A graph for the entire sample was not intelligible given the diverse practices exhibited by each disciplinary group.

The graph for math instructors in Figure 1 reveals a tightly connected central core that suggests a restricted set of overall teaching practices and artifact use in particular.

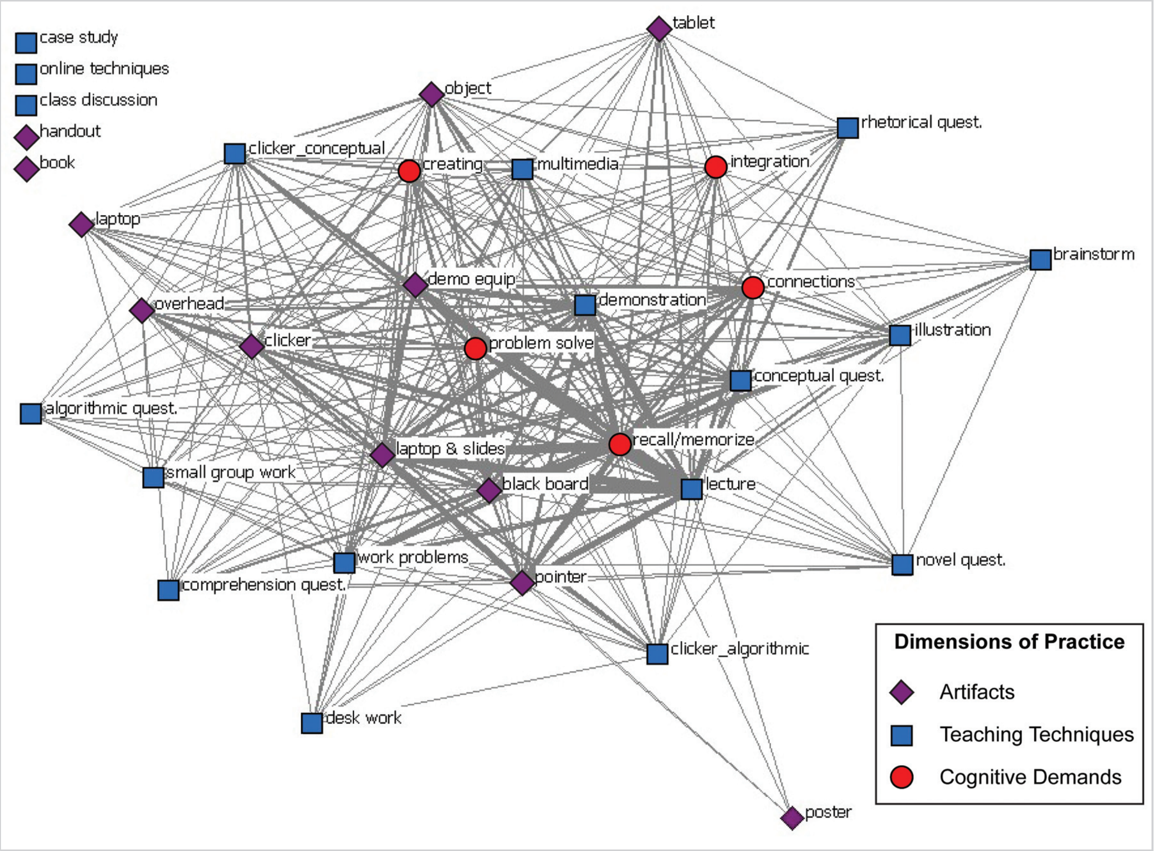
Figure 1
Affiliation Network Graph of Observed Codes for Math Instructors



Note: Unobserved codes are listed in the upper left-hand corner.

Figure 2

Affiliation Network Graph of Observed Codes for Physics Instructors



Note: Unobserved codes are listed in the upper left-hand corner.

As a group, mathematicians demonstrated a primary model of instruction that requires students to problem-solve and recall/memorize information by working out problems and lecturing on the blackboard. This model is supplemented with a range of question styles, including conceptual and algorithmic questions.

The graph for physics instructors in Figure 2 reveals a more diffuse central core than in the graph for math instructors. These physics instructors presented a varied model of instruction that requires students to problem-solve and make connections through the use of demonstrations and demonstration artifacts. In addition, instructors asked students to recall/memorize information while they lectured on the blackboard and used PowerPoint slides with pointers. This primary model was frequently supplemented with the use of clickers, multimedia, questions, and illustrations. The overall model indicates that instructors delivered the course material through lecturing and demonstrations—supplemented by artifacts—that require a wide range of cognitive demands.

We speculate that the contrast in these models reflects differences between the forms of knowledge in math and physics. In the context of the courses included in this study (i.e., undergraduate, mostly lower-division courses), math operates in the realm of ideas and has a very basic form largely dependent on symbol manipulation to prove theorems and other mathematical principles. In contrast, physics is grounded more in the processes of the physical world and has a more applied form, where symbols are used but mostly to model physical processes. Thus, math has basic (i.e., symbolic and non-applied) content with a corresponding model of instruction, whereas physics has applied content modeled through applied instructional practices.

Perceived Constraints on Teaching

Finally, these accounts of teaching practice are incomplete without an understanding of the decision-making process that leads instructors to teach in particular ways. The interview data revealed three primary constraints that instructors claimed exerted a strong influence on their teaching practice: 1) course syllabi and other departments' needs, 2) lack of time, and 3) student characteristics.

Course Syllabi

Respondents noted that course syllabi exerted a strong influence on the content they focused on and the teaching methods they used. Specific topics and their sequencing were often determined in accordance with other departments' needs, particularly in service courses where students from other colleges (e.g., engineering) took undergraduate courses as part of their degree requirements. The resulting syllabi frequently include a wide range of topics in large part because lower level courses build on one another such that certain concepts are required in order to advance to the next course (e.g., calculus sequences).

As a result, instructors felt pressure to cover many topics in a short amount of time, which led to a need to efficiently deliver this content via the didactic lecture method. Additionally, several of these courses had multiple sections such that a common syllabus and exam structure was in place, which meant that instructors could not deviate from this tight schedule without jeopardizing student performance.

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Lack of Time

One well-known constraint that instructors perceive in regards to their teaching activities is that of time, which is limited given the competing demands of their research, service, and advising obligations. The resulting role stress forces instructors to choose among these different responsibilities.

For tenure-track faculty in particular, research activities will sometimes take precedence over additional preparatory time for a class or acquiring new teaching skills. Even for lecturers who are not subject to the pressures of acquiring research funding or publishing, they often have heavy teaching loads that result in a similar lack of time for teaching-related activities.

> …pedagogical reform efforts must be grounded in more detailed accounts of teaching practice.

Student Characteristics

Respondents also cited certain student characteristics as influencing how they approached their teaching, including student reactions to particular classes and teaching methods, and their overall level of preparation for the course. In several cases, instructors "read" their students while teaching the class and responded accordingly based on their reactions.

In addition, several respondents observed that students were poorly prepared for their courses, which necessitated reviewing many basic concepts of the field as well as using many illustrations and examples as a way to "bring to life" the topics being discussed.

Implications for Policy and Practice

The findings presented in this brief have several implications for policymakers and practitioners engaged in math and science education in IHEs. First, because teaching practices vary considerably by discipline, "STEM" as a catch-all category may not make sense in practice. Instead, policymakers and practitioners would do well to focus on discipline-specific practices and workplace conditions when considering pedagogical reforms.

Second, given that single-indicator accounts of teaching methods do not adequately represent the different types of practices being used (i.e., methods, cognitive demand, and artifacts) and how they interact in practice, pedagogical reform efforts must be grounded in more detailed accounts of teaching practice. Detailed accounts can contribute to reform efforts in the following ways:

Provide Insights into the Nature of Educational Reform

Research on educational reform in K-12 schools demonstrates that local practices and traditions will influence whether and how teachers understand and adopt a particular policy or innovation. As a result, prior research recommends that policymakers and practitioners develop a detailed awareness of how these local practices influence reforms at the classroom level.[10]

To do so first requires a deep understanding of local practices. By opening up the proverbial black box of teaching practice using a systems-of-practice approach, it is possible to discern the specific factors that support or inhibit reforms and the forces guiding their adoption, adaptation, or rejection.

Implicate New Ways to Think about Program Design

Insights into the nature of local systems-of-practice can also suggest new ways to think about the design of educational reforms. For example, K-12 reformers focus increasingly on the idea that new policies should exhibit coherence with existing constraints facing teachers—particularly obligations regarding state standards—rather than conflict with them. Researchers argue that new products or innovations should be tailored to the unique practices and workplace conditions of instructors so that innovations are actually viable for classroom use.

In addition, by designing programs with a grounded understanding of local practice, policymakers and educators can determine whether to support or transform existing practices, which is difficult without operating from a baseline portrayal of local practices. User-based design may be particularly important for math and science education reform in IHEs because research suggests that some resistance to pedagogical reforms is due to the perceived antagonism between reform advocates and instructors and advocates' lack of insight into the daily work of instructors.[11]

Identify Leverage Points for Future Interventions

In opening up the black box of teaching, it becomes possible to pinpoint the precise component parts of teaching practices in an IHE classroom. For instance, in this study, instructors consistently cited course syllabi as exerting a strong influence on how they selected content and teaching methods.

In particular, several respondents felt that lecturing methods were the best way to efficiently convey the sheer volume of content in many introductory courses. This suggests that minor changes in course syllabi may reduce the pressure on instructors to cover a large number of topics and rely on lecturing in doing so. With this perspective in mind, an intervention could pair workshops in interactive teaching methods with efforts to change course syllabi in lower-division courses.

> …using a systems-of-practice approach, it is possible to discern the specific factors that support or inhibit reform…

Inform Program Evaluation and Institutional Assessments

Finally, as investments increase in changing teaching practices in math and science, so too does the desire to identify what works and whether particular interventions have met their goals. However, evaluation instruments that solely rely on eliciting the teaching methods that instructors use in a particular class are not sufficiently sensitive to capture the complexities of teaching practice.

With the TDOP instrument, it becomes possible to integrate a systems-of-practice approach into a variety of evaluation designs, including formative evaluations of program implementation and summative evaluations that focus on ascertaining changes over time. Additionally, these snapshots of practice can be used to provide baseline accounts of current conditions for faculty development or institutional assessment purposes.

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However, as interest in assessment and accountability rise in higher education, many IHEs around the globe are becoming increasingly interested in demonstrating the quality of instruction at their institutions. At the present time, indicators such as graduation rates and student learning outcomes are the most common approach to estimating the elusive notion of teaching quality, though researchers are actively seeking better metrics.

It cannot be emphasized enough that the data reported in this brief are not intended to be used in this fashion because equating quality with the use (or lack thereof) of particular teaching techniques is not a valid or defensible proposition. Research suggests that didactic lecturing can be used effectively when tied to a broader pedagogical rationale, while interactive methods such as clickers can be used ineffectively.[12] As a result, the data reported in this brief and the instruments used to collect these data are solely designed to measure descriptive accounts of practice.

Notes

[1] For general information about the learning sciences, see National Research Council, *How People Learn: Brain, Mind, Experience and School*. (Washington DC: National Academy Press, 2000). For information about Peer Instruction and clicker-response systems, see Eric Mazur, *Peer Instruction: A User's Manual*. (New Jersey: Prentice Hall, 1997).

[2] Elaine Seymour and Nancy M. Hewitt, *Talking about Leaving: Why Undergraduates Leave the Sciences*. (Boulder, CO: Westview, 1997).

[3] James P. Spillane, Richard Halverson, and John B. Diamond, "Towards a Theory of School Leadership Practice: Implications of a Distributed Perspective." *Journal of Curriculum Studies* 36, no. 1 (2001): 3-34.

[4] NSF award#: DRL-0814724. For more information about the CCHER study, visit http://ccher.wceruw.org.

[5] See Richard Halverson, "Systems of Practice: How Leaders Use Artifacts to Create Professional Community in Schools." *Educational Policy Analysis Archives* 11, no. 37 (2003). The intellectual roots of systems-of-practice theory can be found in work on distributed cognition (e.g., Edwin Hutchins, *Cognition in the Wild*. [Boston, MA: The MIT Press, 1996]) and activity theory (e.g., Michael Cole and Yrjo Engestrom, "A Cultural-Historical Approach to Distributed Cognition," in G. Salomon [Ed.], *Distributed Cognitions: Psychological and Educational Considerations*, ed. Gavriel Salomon [New York: Cambridge University Press, 1993]).

[6] This instrument is largely based on a previously created WCER instrument intended to capture the *enacted curriculum* of middle school science teachers. See Eric Osthoff, William Clune, Joseph Ferrare, Kerry Kretchmar, and Paula White, *Implementing Immersion: Design, Professional Development, Classroom Enactment and Learning Effects of an Extended Science Inquiry Unit in an Urban District*. (Madison, WI: University of Wisconsin–Madison, Wisconsin Center for Educational Research, 2009).

[7] Three instructors were only observed once due to scheduling conflicts.

[8] For additional information about the methodology of the CCHER project, visit http://ccher.wceruw.org.

[9] The strength of affiliation between two codes refers to the number of five-minute intervals in which the codes are co-present.

[10] Michael Fullan, *Leading in a Culture of Change*. (San Francisco, CA: Jossey-Bass, 2007).

[11] Charles Henderson and Melissa H. Dancy, "Physics Faculty and Educational Researchers: Divergent Expectations as Barriers to the Diffusion of Innovations." *American Journal of Physics (Physics Education Research Section)* 76, no. 1, (2008): 79-91.

[12] Nira Hativa, "What is Taught in an Undergraduate Lecture? Differences between a Matched Pair of Pure and Applied Disciplines." *New Directions for Teaching and Learning*, 64, (2005): 19-27; Chandra Turpen and Noah D. Finkelstein, "Not All Interactive Engagement is the Same: Variations in Physics Professors' Implementation of Peer Instruction." *Physical Review Special Topics – Physics Education Research* 5, no. 2, 020101 (2009): 1-18, http://prst-per.aps.org/pdf/PRSTPER/v5/i2/e020101.

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