Changing the Teaching Culture in Introductory STEM Courses at a Large Research University

By Geoffrey L. Herman, Jennifer C. Greene, Laura D. Hahn, Jose P. Mestre, Jonathan H. Tomkin, and Matthew West

We describe a major transformation in teaching large introductory courses in the sciences and engineering at the University of Illinois at Urbana-Champaign, impacting over 17,000 students yearly. The transformation was emergent, not prescribed, and occurred through two programs that included both engineering and science departments. Working collaboratively in Communities of Practice (CoPs), made up of a small number of faculty and teaching professionals formed within departments, faculty adopted and implemented evidence-based instructional practices with the goal of sustaining them over time. To make the reform process understandable to research faculty, we adopted the adage of "teach like you do research," meaning not only using iterative, evidence-based decision making but also engaging in a scholarly, collaborative community that pushes each individual member toward excellence. Another essential feature of the reform was embedding faculty members within the CoPs who had both knowledge of and a track record of implementing evidence-based reforms in their courses to serve as resources to the CoP. We describe the course-reform process and lessons learned and provide evidence for the success of our efforts.

Despite mounting documentation that evidence-based instructional practices (EBIPs) are more effective for teaching STEM (science, technology, engineering, and mathematics) gateway courses than traditional lecture approaches (Freeman et al., 2014), significantly changing traditional teaching practices at research universities remains a daunting task (Beach, Henderson, & Finkelstein, 2012). Reforms made to gateway STEM courses are typically based on instructors' biases and hunches about good practices, rather than on research evidence, perhaps because STEM faculty knowledge of EBIPs is neither expected nor rewarded (Handelsman et al., 2004). Even when faculty reform a course by adopting some EBIPs, it is typically initiated and "owned" by the instructor teaching the course at the time, and progress is lost when a new instructor takes over the course.

We report here on two related, successful efforts to implement EBIPs in large gateway undergraduate STEM courses in 14 departments at the University of Illinois, using a Community of Practice (CoP) model to address such barriers to change.

Institutional change in postsecondary STEM education

Recent literature on changing instructional practices in STEM highlights the ineffectiveness of "top-down" mandates and of isolated faculty development workshops that disseminate "best practices" (Henderson, Beach, & Finkelstein, 2011). These approaches are likely ineffective because they fail to address the implicit beliefs that drive instructional decisions (Hasweh, 1996; Luft & Roehrig, 2007; Tsai, 2002). Recent studies have suggested that we can address these mindsets by focusing on affecting faculty's beliefs and motivation, as well as the broader institutional culture (Beach et al., 2012; Brownell & Tanner, 2012; Finelli & Millunchick, 2013; Finelli, Richardson, & Daly, 2013; Henderson & Dancy, 2007; Siddiqui & Adams, 2013).

The CoP model offers a way to encourage both individual and collective change. CoPs provide a highly collaborative organizational structure that is intended to last and thereby promote long-term situated learning (Lave & Wenger, 1991; Wenger, 1998; Wenger, McDermott, & Snyder, 2002). Such collaborative cultures can lead to the forging of new beliefs and identities (Keys & Bryan, 2001) as well as curriculum reform (Finelli & Millunchick, 2013; Villachia, Marker, Plumlee, Huglin, & Chegash, 2013).

We therefore focused on forming CoPs around each of our targeted gateway courses to create sustainable, evidence-based instructional change. Two notions guided our reform efforts. First, building on the strong culture at the University of Illinois of STEM research collaborations, we encouraged faculty to "teach like you do research," meaning collaboratively and using evidence to guide reform. The second notion was joint ownership: Members of the CoP explicitly agree to use the collaboratively created materials and pedagogies in future offerings of the course.

Description of SIIP and WIDER reform efforts

The Strategic Instructional Innovations Program (SIIP) is a competitive, internally funded grant program for improving undergraduate instruction in the College of Engineering. Since 2012 it has awarded nearly 3 million dollars through 28 grants across nine departments (Aerospace Engineering, Bioengineering, Civil and Environmental Engineering, Computer Science, Electrical and Computer Engineering, Industrial and Enterprise Systems Engineering, Material Science and Engineering, Mechanical Science and Engineering, and Physics) with 12 interdisciplinary CoPs. The SIIP administrative team consists of a director and several Education Innovation Fellows (EIFs), faculty members with a track record of instructional innovation. Of the 11 who have been EIFs, nine are research-active, tenured faculty, and two are senior specialized teaching faculty.

An annual call for proposals to SIIP encourages teams of at least three faculty to form a CoP, committing to meet weekly during the year to design and implement a curricular innovation. If a preproposal is approved by the administrative team, an EIF works with the CoP to develop a full proposal. The proposal evaluations are based on evidence of support from departmental administration, collaborative development and ownership of the proposal and project, valued faculty and student outcomes, sustainability and positive trajectory, and a viable work plan. Grants have ranged from $5,000 to $100,000.

An EIF is then embedded in each funded project, attending the weekly meetings and serving as a resource to the CoP. The EIFs also meet weekly to share updates and brainstorm solutions to problems in the CoPs. This structure was intended to create a sense of partnership between the administrative team and CoPs.

Funded CoPs undergo a midyear evaluation and submit a year-end project report along with their application for continued funding (up to 3 years). During the midyear evaluation, CoPs self-assess their progress on their own stated goals as well as on collaborative development, departmental support, and outlook for sustainability and scalability of their efforts. The administrative team performs the same assessment. The CoP, administrative team and department leadership then meet to jointly discuss the CoP's progress; each CoP receives a written summary of the evaluation. The administrative team also reviews the CoPs' year-end reports and provides feedback and recommendations for further funding. Although these measures are time intensive, they have resulted in greater accountability among CoPs, as well as increased clarity of expectations for all parties. Indeed, as a result of the project evaluations, six projects were discontinued.

WIDER is an NSF-funded grant from the program bearing the acronym (Widening Implementation and Demonstration of Evidence-Based Reforms). We are in the third year of the 3-year grant that funds five departments from Liberal Arts and Sciences (Mathematics, Molecular and Cellular Biology, Integrative Biology, Geosciences, and Chemistry) and six from Engineering (Physics, Computer Science, Mechanical Science and Engineering, Electrical and Computer Engineering, Materials Science and Engineering, and Civil and Environmental Engineering). WIDER is managed by the five principal investigators, three of whom are from Engineering; one from Liberal Arts and Sciences; and one, an evaluation expert, from the College of Education. Like SIIP, WIDER requires teams to form CoPs and embeds one of the PIs within each CoP to serve as a resource. The evaluation specialist embeds trained graduate students in the CoP to evaluate the functioning of the CoP and the success of the underlying program model.

Due to the overlap and similarities in operation between SIIP and WIDER, for the remainder of this article we discuss the CoPs in general without their SIIP or WIDER designations. The composition of the 19 CoPs goes as follows: Six are comprised of tenured or tenure-track faculty, six are comprised of nontenure-track teaching faculty, with the remaining seven teams having a combination. As discussed in the following section, the effectiveness of CoPs is not a function of participant rank or status, but rather of the trust and working relationships among the members.

Evidence for successes and failures

Evaluation metrics

We used both qualitative and quantitative metrics to gauge the effectiveness of the CoPs: yearly evaluations of the CoPs; amount of money spent on the CoP's reform efforts; student perspectives of reforms by the WIDER evaluation team; EIF role as mentors/connectors; classroom observations of the CoP's implementation of the EBIP; the degree to which adopted EBIPs spread to other CoPs; number of scholarly, education-related publications by members of the CoPs; number of education-related federal proposals submitted/funded/authored by CoP members; and whether the innovations continued after funding ended.

Yearly evaluation of SIIP/WIDER CoPs

The yearly evaluation performed by the leadership team assigned ratings to each CoP along five dimensions: administrative support (e.g., has the administration accommodated teaching schedules?), collaborative development (e.g., do all CoP members agree on the use of best practices?), faculty outcomes (e.g., were the faculty learning to teach better?), student outcomes (e.g., were the students learning better?), and sustainability or trajectory (e.g., does the team have a plan to continue their efforts after funding stops?). The leadership team was composed of educational researchers, faculty development personnel, and faculty with a track record of using EBIPs. Each project was evaluated along the five dimensions by at least three members of the leadership team to ensure fairness of decision making and ratings. At least one of those raters attended the weekly meetings of the CoP being evaluated and was deeply familiar with the CoP's team dynamics and achievements. On the basis of the evaluation, the leadership team assigned each CoP a rating of Outstanding, Commendable, Satisfactory, Improvement Required, or Not Acceptable. Functional CoPs received ratings of Satisfactory, Commendable, or Outstanding, whereas dysfunctional CoPs received ratings of Not Acceptable or Improvement Required.

Effect of funding level

Monetary support for the CoPs can fund summer salary and research assistants to help in the development/implementation of the EBIP, travel to conferences to present results, and other project expenses. To study the effect of funding on the performance of the CoPs, we calculated a correlation between the amount of funding each CoP received and the performance of those CoPs on the annual review rubric. Using a Spearman Rho statistic to account for the dichotomous rating scale (functional vs. dysfunctional), we found no correlation ($\rho = -0.19$) between funding level and performance.

EIFs as mentors and connectors

The EIFs have been central to the success of SIIP. Because they are familiar with EBIPs, they are able to offer their teams valuable, practical advice that helps move their projects forward efficiently. The EIFs are also able to cross-pollinate ideas, essentially helping teams copy successful innovations. As one EIF explained: "The peer aspect is a key element; if an administrator were pushing teaching approaches, the model would not be as successful." Another noted: "From an outsider's view, it's much simpler to think creatively about their projects because I'm constrained neither by past experience with the topics, nor by the fear of incurring the social cost of a bad idea." The EIFs' active engagement brings visibility and increased status to teaching as a scholarly activity.

Classroom observations

To gauge the degree of interactivity in foundational STEM courses, 49 courses were observed, with class sizes ranging from 40 to 600 students, with a mean of 163. Sixteen of the 49 courses were taught by members of a functional CoP, with the remaining 33 courses taught by members of dysfunctional CoPs or non-CoP instructors. The Classroom Observation Protocol for Undergraduate STEM (COPUS; Smith, Jones, Gilbert, & Wieman, 2013) was used to examine how both the instructor and the students spent class time. Activities are logged at 2-minute intervals for the presence or absence of specific activities—for example, whether the instructor is lecturing or guiding a discussion and whether students are passively listening or engaged in small-group conversations. Classes were observed once by two trained observers, with high agreement between them (Cohen's Kappa = 0.875, equivalent to those reported in Smith et al., 2013). An instructor was considered to be *guiding* in a 2-minute observation interval if any student-centric activity was recorded in COPUS (e.g., posing a question, guiding group work); the 2-minute period was designated as *presenting* if the instructor was lecturing or using a video or demonstration. The ratio between the number of guiding to presenting periods was used as a metric for describing the relative student-focused nature of the teaching of that class. A similar ratio, *working/receiving*, was computed for students, with *working* meaning that students were engaged in activities such as answering a question or working in groups, whereas *receiving* consisted largely of listening. Functional CoP instructors spent significantly more time guiding than presenting compared to their dysfunctional CoP, or non-CoP counterparts, as indicated by a Wilcoxon rank-sum test comparing the ratios for the two groups ($Z = 4.499$, $p < .001$, effect size 0.643). Similarly, students in classrooms taught by functional CoP instructors spent significantly more time working than receiving when compared to dysfunctional CoP instructors, as indicated by a Wilcoxon rank-sum test comparing the ratios for the two groups ($Z = 3.974$, $p < .001$, effect size 0.568). Fully a third of the dysfunctional CoP classes had no time with students working (the working/receiving ratio is zero), whereas all functional CoP lectures incorporated some student working. These findings are independent of class size and instructor rank.

Spread of innovations across CoPs

We observed the spread of innovation with many different EBIPs, such as the use of personal response systems in large lectures or the use of more frequent testing. We illustrate the spread of innovations with one EBIP: context-rich collaborative problem solving (students working in teams to solve difficult, real-world problems). As shown in Table 1, this innovation originated in the Mathematics Department and was adopted first into the Theoretical and Applied Mechanics (TAM) CoP by an EIF ("Dr. EIF1"). From there it was transmitted by connecting EIF faculty ("Dr. EIF2" and "Dr. EIF3") to CoPs in Electrical and Computer Engineering (ECE), Materials Science and Engineering (MatSE), and Computer Science (CS). In total, 27 faculty teaching 11 courses in four departments have implemented context-rich collaborative problem solving for multiple semesters. This example shows the effectiveness of CoPs in implementing innovations and the need for faculty "connectors" (EIFs) who can link CoPs together.

Project-related publications

The CoPs have begun actively publishing about their efforts. Participants have published five journal articles, 50 peer-reviewed conference papers, one master's thesis, one peer-reviewed book chapter, and one textbook. These 58 publications represent 64 unique authors, of which 38 had never previously published on education innovations or research.

Project-related grant proposals

Over the past 3 years, participants have submitted 21 external STEM education grant proposals (including WIDER itself), totaling over $22 million. Eight of these proposals have been funded for a total of $6.0 million. These proposals were submitted by 46 unique PIs—33 STEM faculty and 13 education faculty. Critically, 29 of these STEM faculty had never submitted an education proposal prior to joining SIIP/WIDER, representing an eightfold increase in the number of SIIP/WIDER STEM faculty who have submitted such proposals.

Longevity of innovation after project ends

The funding from SIIP and WIDER to individual CoPs has a limit of 3 years. An important measure of success is the extent to which CoPs remain active without funding. As shown in Table 2, 80% of SIIP CoPs remained functioning after funding ended, suggesting that the CoPs had achieved a degree of sustainability. These results also show that only 33% of the SIIP CoPs that ceased functioning did so when their funding was terminated, suggesting again that funding was not a primary concern for the CoPs. For the eleven WIDER CoPs, eight (73%) are still functioning and three (27%) ceased, all voluntarily. Because the WIDER project is still ongoing, the analysis of funding outcomes is not discussed here.

What about student outcomes?

Although this article is about changing the teaching culture among research-intensive faculty and not about examining student outcomes, we include here a brief summary list of some preliminary student outcome measures because they will likely be of interest to the readership.

- The Chemistry, Integrated Biology, and Electrical and Computer Engineering CoPs have adopted a workshop-based learning program (Fullilove & Treisman, 1990) that is improving students' sense of belonging in the department, as measured by Hoffman, Richmond, Morrow, and Salomone's (2002) survey, and has doubled the retention rate of African American students and almost completely eliminated the retention gap for women (Adams & Lisy, 2007; Minin, Varodayan, Schmitz, Faulkner, & Herman, 2016).

TABLE 1

Spread of the context-rich collaborative problem-solving innovation to an eventual 11 courses and 27 faculty.

Pathway of spread	Connector	Courses converted	Faculty involved
Math dept → TAM CoP	Dr. EIF1	3	7
TAM CoP → ECE CoP	Dr. EIF2	2	9
TAM CoP → MatSE CoP	Dr. EIF3	2	6
TAM CoP → CS CoP	Dr. EIF1	4	5
Total		11	27

Note: TAM = Theoretical and Applied Mechanics; EIF = Education Innovation Fellows; ECE = Electrical and Computer Engineering; MatSE = Materials Science and Engineering; CS = Computer Science; CoP = Communities of Practice.

TABLE 2

Contingency table for SIIP CoP outcomes.

	Funding ended	Funding continued	Total
CoP still functioning	8	5	13
CoP ceased	2	4	6
Total	10	9	19

Note: SIIP = Strategic Instructional Innovations Program; CoP = Communities of Practice.

- Using a combination of peer instruction, collaborative learning, and computation/simulation tools, the Materials Science and Engineering CoP improved students' performance on their final exams by six percentage points, a statistically significant difference with moderate effect size (Cohen's $d = 0.44$; Kononov et al., 2017; Mansbach et al., 2016).
- The adoption of a mastery-based online learning system into courses by the Theoretical and Applied Mechanics CoP approximately doubled the number of As earned by students on the final exam and reduced the failure rate on the final exam in half (West, Silva Sohn, & Herman, 2015; West, Herman, & Zilles, 2015).
- The incorporation of context-rich collaborative problem solving (Heller & Hollabaugh, 1992; Heller, Keith, & Anderson, 1992) into courses by Theoretical and Applied Mechanics, Material Science and Engineering, Electrical and Computer Engineering, and Computer Science has led to improved student satisfaction, communication skills, and connectedness with peers in courses (Essick, Silva Sohn, West, Mercier, & Herman, 2016; West & Herman, 2015).
- The integration of various effects that have been shown to independently help students learn within a web-delivered problem-solving treatment by the Physics CoP resulted in better performance in near-transfer and far-transfer problems when compared with a traditional homework-style, web-delivered treatment consisting of solving similar web-based problems with immediate correctness feedback and unlimited tries (Gladding, Gutmann, Schroeder, & Stelzer, 2015).

Lessons learned

Our experience with systemic reform efforts yields some strategies for those wishing to implement evidence-based reforms at other large research institutions.

- *Rely on models that faculty understand*. Our mantra of using collaboration to "teach like you do research" builds on the social and intellectual norms of our faculty. Faculty research and scholarly work in STEM is done collaboratively with graduate students, postdocs, and other faculty. In research groups team members experiment, discuss findings, and use evidence to plan future research. That implementing EBIPs should follow a similar model should not be a difficult case to make to faculty.
- *Advocate for a commitment to joint ownership*. Collaborative approaches to instructional reform increase both the quality and sustainability of the reforms. In contrast, one-shot, or "lone-ranger" approaches to reform rarely work. For example, campus teaching centers often bring in outside speakers to promote EBIPs, and some faculty leave those talks energized. However, when faced with working alone and spending lots of time making wholesale changes in their course, their ambition soon wanes (Henderson & Dancy, 2009). Even if such a lone-ranger approach succeeds, the reform is owned by the individual who designed it and is unlikely to be adopted by those who follow.
- *Embed pedagogical experts in the CoPs*. Their primary function is to educate the team about EBIPs that could be adapted to the local context. In addition, they can make connections to other CoPs, thereby promoting the spread of innovations across different CoPs.
- *Institute an evaluative process*. Evaluating the impact of EBIPs on student learning is complicated. Focusing on evaluating faculty practices over time can provide useful feedback that can subsequently optimize the intervention. The COPUS instrument is a promising way to collect data on faculty practices.

Thus far we have been successful in helping 14 departments implement EBIPs, such as flipped classrooms with prelectures, use of active learning with clickers, problem-based learning, and context-rich collaborative problem solving. We were somewhat suprised that level of funding was completely uncorrelated with the functionality of a CoP or the implementation of an EBIP. Having available time for a faculty member to devote to the reform is perhaps a better indicator of success; thus some faculty release time could serve as a catalyst. Finally, support of the administration (i.e., department heads, associate deans, and deans) is important—not because of top-down mandates to implement reforms, but more because the administration sends a message that quality of teaching is important. ■

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