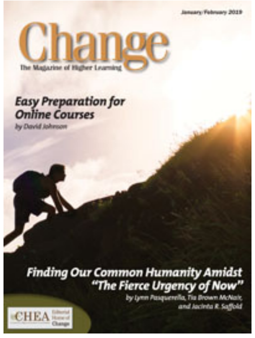

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Keep Your Friends Close and Your Colleagues Nearby: The Hidden Ties that Improve STEM Education

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Keep Your Friends Close

and Your Colleagues Nearby: The Hidden Ties that Improve STEM Education

By

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In Short

- Using a Communities of Practice model, the University of Illinois at Urbana-Champaign has implemented Evidence Based Instructional Practices (EBIPs) across large-enrollment introductory STEM courses in 13 science and engineering departments impacting over 17,000 students yearly.
- A social network analysis of the spread of EBIPs at Illinois indicates that faculty mentors embedded in departmental Communities of Practice were the catalysts for the rapid spread of reforms.
- Encouraging a "teach the way you do research" approach resonates with professors at a research university in terms of adopting and refining evidence-based reforms.
- Cultural change among many faculty members appears to have taken hold as evidenced by number of educational publications by STEM faculty members, federal education proposals written and funded, and sustainability of the innovations after initial funding ended.

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A science department on our campus has received numerous national awards for excellence in undergraduate teaching. The secret to their success? For nearly two decades, they have collaboratively used evidence-based instructional practices (EBIP) in their introductory level courses. Despite these successes and efforts to spread their EBIP, no other departments followed this department's lead. Then, suddenly six years ago, many instructors from other departments began adopting EBIP in their classrooms.

What was the catalyst for this change? And why had previous attempts at institutional change failed? We aim to answer these questions by analyzing our efforts to transform the teaching practices in large-enrollment science and engineering introductory courses on our campus.

The challenges of changing teaching on our campus reflect the general challenges of changing the teaching culture at large research universities (Kezar, Gehrke, & Elrod 2015). Research is valued above teaching; faculty are trained and rewarded to be researchers rather than teachers. Consequently, faculty are unaware of EBIP or are hesitant to commit the time and energy to learn how to implement them well. Further, faculty teach in isolation (Spalter-Roth, Mayorova, Scelza & Vooren, 2010), with each instructor deciding how they wish to teach their course. Even when an individual faculty member might implement EBIP into a course, their changes can be easily ignored by the next instructor, stifling innovation and iterative improvement.

Despite these challenges, after six years of working collaboratively, we were surprised at the magnitude of the program: 231 faculty and teaching professionals from 28 departments at the University of Illinois have implemented EBIP to transform 58 introductory courses in 13 STEM departments, impacting over 17,000 students each year. This reform effort was led by a small group of faculty and teaching professionals who served as catalysts for change. These change agents were embedded in multiple departmental *communities of practice* (CoP; Wenger, McDermott, & Snyder 2002). Comprised of several faculty/teaching professionals, these CoPs collaboratively worked together deciding what EBIP to incorporate into a large introductory course or series of related courses and committing to continue using the EBIP implemented by the other members of their community.

To understand why this change strategy was effective, we turned to social network analysis. Social network analysis argues that change and organizational learning can be brokered through two types of social interactions (Daly, 2010; Burt, 2004): 1) *strong ties* between small groups of people that promote learning and incremental improvement and 2) *bridging ties* between disparate groups of people that promote the spread of new ideas and innovations. We argue that our efforts were successful because the structure of our program provided both the strong and bridging ties that faculty previously lacked.

Research-Based Frameworks for STEM reform

The National Research Council (Singer, Nielsen, & Schweingruber, 2012) synthesized features of successful STEM transformations in higher education. They recommend that instructors design instruction that builds on what students know in ways that optimize students' engagement, incorporates collaborative work between students, uses technologies to make students' thinking visible to help instructors target students' learning difficulties, and broadens learning goals to include flexible transfer of learning across contexts and deep conceptual understanding. We include all of these practices under our definition of EBIP.

Beach, Finkelstein and Henderson (2012) proposed a framework for describing efforts to promote the adoption of EBIP in STEM based on an extensive literature review. Presented as a 2x2 grid, the columns denote Prescribed Reforms versus Emergent Reforms, and the rows denote the entity doing the reform, namely Individuals versus Environments and Structures. They found that while three of the quadrants had about equal number of reform efforts (~30%), only 8% of articles belonged to the Emergent/Environments and Structures quadrant. While there are notable exceptions, efforts in the other three quadrants have been generally ineffective at creating sustained change in STEM education across higher education. As will be illustrated below, the Emergent/Environments and Structures quadrant offers the opportunity to shape reform that is both sustainable and "palatable" to scientists and engineers. We explain the mechanism behind this successful effort with evidence from social network analysis.

The reform effort at Illinois was emergent, not prescribed; CoPs within departments determined what EBIP to implement. The effort was also environmental, with faculty within each CoP being supported by the other faculty within their community and linking with other faculty across CoPs by embedded "mentors" who served as change agents.

This structure is similar to the transformation model described in Wieman, Perkins and Gilbert (2010), a similarly successful reform at another large research university. Wieman's effort focused on academic departments as the locus of change connected by postdocs who were knowledgeable about EBIP. While our communities were located within departments, communication across communities occurred through embedded faculty mentors that played a role similar to the Wieman postdocs. Unlike Wieman and colleagues, however, we found that the level of monetary resources provided to departmental CoPs did not correlate with successful innovations (Herman et al., 2018).

The Reform Efforts at Illinois

The STEM reforms at Illinois have largely targeted introductory courses and were accomplished with two different but related programs. The first is the Strategic Instructional Innovations Program (SIIP) housed in the College of Engineering (Herman, et al., 2018). This program solicits competitive proposals from groups of faculty members in departments wishing to reform a course. Successful proposals are funded for two years, with the first year devoted to designing the reform and the second year devoted to implementing the reform and obtaining feedback for improving it.

Since its inception in 2012, 28 grants have been awarded to 9 departments totaling $3 million, with grants ranging from $5K to $100K. Each proposal was also assigned a team mentor—a faculty member with knowledge about EBIP and a track record of STEM reform who is embedded in the CoPs to provide expert support. As will be discussed below, the 11 mentors play a pivotal role in the Illinois' reform effort, both in terms of ensuring that reforms are based on EBIP and in terms of disseminating instructional innovations across departments.

The second program is based on a grant funded by the National Science Foundation's Widening Implementation & Demonstration of Evidence-Based Reforms (WIDER) program (Herman, et al., 2018). The goals of the WIDER and SIIP programs are similar, with WIDER encompassing reforms in introductory courses in departments across both Engineering (Material Science and Engineering, Civil & Environmental Engineering, Computer Science, Physics, Electrical & Computer Engineering, and Mechanical Science &

Engineering), and Liberal Arts and Sciences (Geosciences, Chemistry, Biology, and Mathematics). The four principal investigators served as mentors for these projects. As with SIIP, a WIDER reform effort must be organized around a CoP of faculty and/or teaching professionals who agree to meet weekly to discuss and adopt one or more EBIP in the introductory course.

Communities of Practice (CoP)

Each SIIP and WIDER team is organized around a CoP (Wenger, McDermott & Snyder, 2002) as a way to encourage individuals to work toward common collective goals. The COP meets weekly with the goal of implementing a sustainable EBIP in the target course that is jointly owned by the group and by the department. In this way the members of the CoP and the department's administration commit to teach the course with the instituted reform for the foreseeable future.

CoP members collectively identify, adapt, and implement the desired EBIP as well as devise methods for evaluating effectiveness. The EBIP selected by each CoP is not prescribed but rather emerges from the many discussions within the CoP, which include reviewing scholarly articles available for the EBIP under consideration and evaluating suggestions from the embedded mentor. The motto followed in all CoPs and encouraged by the mentors is to "teach the way you do research," which discourages individuals from proposing teaching methods based on hunches or personal experience without regard for evidence on effectiveness. Since research faculty understand how research is done (e.g., building on prior work, collecting and analyzing data), improving teaching practices by relying on evidence is not a difficult practice to "sell" in the CoPs.

The CoP model also encourages emergent reforms since the CoP members work collaboratively toward a common goal and share joint ownership; in fact, we have found that failure in a CoP's ability to implement and sustain a reform is almost always due to one group member taking on a "dictatorship" role to advance their instructional agenda, or to groups not meeting weekly and having one member devise the reforms in isolation and passing them to the rest of the group to use (which they don't).

EBIP Adopted and Evidence of Impact

SIIP/WIDER have sparked the rapid spread of EBIPs across the two colleges and has created a thriving community of faculty invested in improving undergraduate instruction. Thirty instructors from five different departments integrated context-rich collaborative problem solving into their courses (Essick et al., 2016). Similarly, in the first three years of SIIP/WIDER, classroom response systems (i.e., clickers) and peer instruction (Crouch & Mazur, 2001) were used in 16 SIIP/WIDER-affiliated courses. Faculty have also adopted a range of other EBIP such as case studies (Davis & Yadav 2014), guided-inquiry learning (Eberlein, et al., 2008), workshop instruction (Preszler 2009), and project-based learning (Eberlein et al., 2008). SIIP/WIDER

"The motto followed in all CoPs and encouraged by the mentors is to 'teach the way you do research,' which discourages individuals from proposing teaching methods based on hunches or personal experience without regard for evidence on effectiveness.

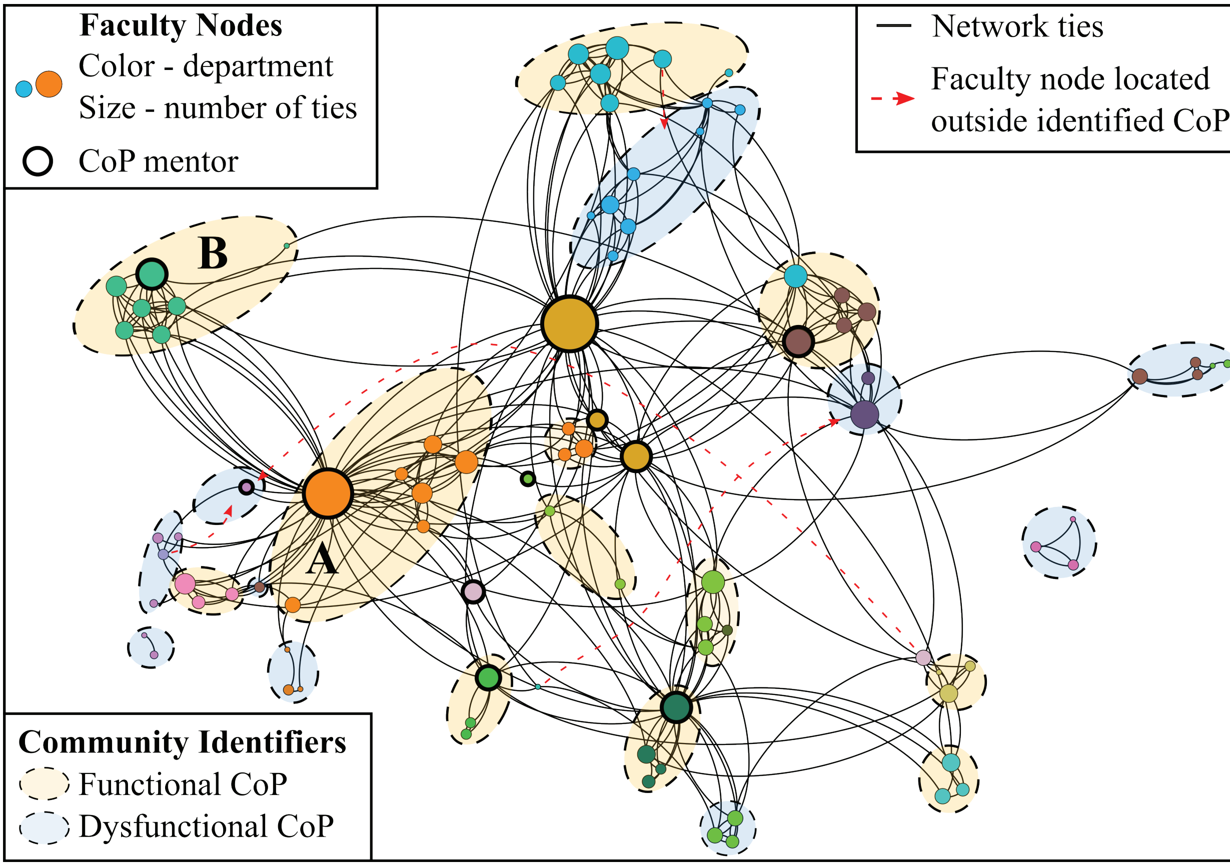
faculty have also become engaged in the process of translating research into practice. For example, teams of faculty are developing mechanisms to enable frequent testing regimes (Roediger & Butler, 2011) and second-chance testing to promote mastery (Diegelman-Parente, 2011). Others are exploring how to create more holistic education, integrating instruction on writing, communication, and creativity into core STEM courses.

Spread of Reforms via Mentors: Social Network Analysis of Spread of Reforms

The mentors meet separately on a weekly basis to share information and discuss progress in the CoPs. Often the mentors share details about a particular EBIP that a CoP is adopting/implementing, and if/when relevant, a mentor may share that information with their assigned CoP. An individual may discuss a problem or issue that a CoP has been attempting to address and seek advice from the others to take back to the CoP. EBIP also spread from this type of dissemination in an emergent rather than prescribed fashion. The embedded mentors, who were initially viewed as simply a resource to help the CoPs, turned out to be much more important in terms of spreading instructional innovations across departments and courses.

To understand the importance of mentors in spreading reform we made use of social network analysis (Figure 1). The visualization was generated from surveys collected from 100 faculty from 18 departments (Ma, et al., 2018). Nodes (circles) with the same color represent faculty from the same department. Ties (lines) between nodes indicate *teaching collaborations* between those nodes. Nodes were arranged algorithmically based on the number of ties between nodes (Noack 2007). Dashed ovals indicate which faculty belong to each of the 22 CoPs in our study. If a faculty node lies

Figure 1. Algorithmic visualization of the teaching social network of faculty. Communities of Practice (CoPs) of faculty are connected by CoP mentors. Functional CoPs have more internal, strong network ties and sustainably use EBIP. CoP mentors bridge the CoPs, spreading knowledge of EBIP.



outside its official CoP, a dashed line with an arrow indicates the CoP to which they belong.

Figure 1 shows two types of social network ties. A strong tie is defined in social network theory as a frequent interaction between two individuals characterized by trust-building over an extended period of time (Burt 2004). A weak tie is defined as an infrequent or indirect interaction (Burt 2004). Although they require little time or effort, weak ties are instrumental in sparking creativity and fostering innovation. In Figure 1, strong ties are those within the ovals, denoting interactions among members of a CoP within a single department. Weak ties are those between the mentors (denoted by colored circles with solid black lines on their circumference) and individual faculty within many different CoPs. Because these weak ties were created by bridging mentors to many other faculty members in different COPs in the network, we refer to these weak ties as *bridging* ties.

Not all CoPs were successful. CoPs were rated as functional or dysfunctional based on annual performance reviews (Ma et al., 2018). We use these evaluations to compare the network characteristics of CoPs that are sustainably and communally using EBIP (Functional CoPs—yellow ovals) with those that do not (Dysfunctional CoPs—blue ovals). The importance of strong ties is revealed by the greater average number of ties within a CoP: Functional CoPs have twelve ties on average as compared to four ties for dysfunctional CoPs.

These ties are strong for several reasons: members of these CoPs share a common goal of reforming a course, they generally share disciplinary affiliations, and they interact frequently (typically on a weekly basis). The diagram also reveals the bridging ties between the CoPs. Almost 70% of collaborative ties (100 of 142) that reach outside the CoPs are to mentors, indicating that CoP members rarely have teaching ties outside of their CoPs. The mentors play an enabling role in the network, allowing information and practices to spread across CoPs. For example, CoP A was content with ineffectually assigning teams randomly during collaborative learning exercises, having spent several iterations to work out the logistics of that method. Meanwhile, CoP B was using an evidence-based team-building tool (Layton, Loughry, Ohland, & Ricco, 2000). The CoP-mentor relationships enabled CoP A to learn about the team-building tool used in CoP B and begin using it.

Social network analysis reveals otherwise hidden structures that have previously thwarted systemic change in undergraduate STEM teaching (Kezar, Elrod, & Gehrke 2015, Quardokus & Henderson, 2015). This hidden structure can

Figure 2. Four Quadrant Model of Teaching Networks. Efforts to improve faculty teaching practices tacitly promote certain types of network ties, but generally fail to promote both the strong and bridging teaching ties needed for sustainable change.

	Does not promote bridging ties	Promotes bridging ties
Does not promote strong ties	Q1: Traditional teaching structures	Q2: Center for teaching and learning
Promotes strong ties	Q3: Discipline-based education researchers	Q4: Course-centric CoPs connected by mentors

Table 1. 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

best be understood through the four quadrant model shown in Figure 2. Historically, teaching is done in intense isolation at the university level (Quadrant 1), with faculty maintaining sole jurisdiction over their courses with little input from their peers (Spalter-Roth, et al., 2010). This lack of connectivity enables the status quo that resists adoption of EBIP. The lack of strong ties leads faculty to quit using EBIP or to implement them poorly, and the lack of bridging ties reduces their exposure to peers who are successfully using EBIP (Henderson, Dancy & Niewiadomska-Bugai, 2012).

Centers for teaching and learning at universities disrupt the status quo by providing bridging teaching ties (Quadrant 2) but generally fail to provide the strong ties that change practices (Henderson, Dancy & Niewiadomska-Bugai, 2012). Efforts such as that of the successful science department described at the start of this article created strong ties through discipline-based education research but failed to create bridging ties that enabled their ideas to spread (Quadrant 3). The SIIP and WIDER efforts described here created both strong and bridging ties (Quadrant 4) that enabled both departmental reforms and the spread of innovations across departments.

Evidence of Cultural Change

Although it is difficult to quantify "cultural change" in the STEM departments undergoing introductory course reform, there are strong indications that there is a shift in attitude within departments toward adoption and sustainment of EBIP (Herman et al., 2018). The indicators include:

- Educational publications related to reform efforts. The CoPs have taken the "teach the way you do research" motto to heart and have begun actively publishing educational articles on their reforms. Participants have published 14 journal articles and 57 peer-reviewed conference papers. These 71 publications represent 212 unique authors, a majority of which had never previously published on education innovations/research.
- Proposals related to teaching and learning. Another measure of a changing teaching culture in STEM departments is interest in procuring funding for additional reforms. Over the past six years, participants have submitted 37 external STEM education grant proposals (including WIDER itself), totaling over $28 million. Fifteen of these proposals have been funded for a total of $7.4 million. These proposals were submitted by 54 unique interdisciplinary Principal Investigators. Critically, a majority of these faculty had never submitted an education proposal prior to joining SIIP/WIDER, representing a substantial increase in the number of SIIP/WIDER STEM faculty who have submitted such proposals.
- Sustainability of innovation following project conclusion. The funding from SIIP and WIDER to individual CoPs has a limit of three years. An important measure of success is the extent to which CoPs remain active without funding. One measure of sustainability is an evaluation that was conducted of the SIIP projects that were funded from 2012 to 2015. As shown in Table 1, 80% of these 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 that funding was not a primary concern for the CoPs (and in fact SIPP funding level was not statistically significantly correlated with success). 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.
- Classroom observations. 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. Sixty large introductory STEM courses were observed, including both courses involved in the reform effort and others. There were stark differences in how instructors conducted their lessons. Instructors from functional CoPs spent more time guiding students than other instructors and less time lecturing (both significant

at $p < 0.001$, and with effect sizes of 0.94 and 1.40, respectively, Tomkin et al., in review). This impacted what the students did in the classroom: students in the classes of functional CoP instructors were recorded as "working" (engaged in active learning) at three times the rate as in the other (non-CoP) classes.

Although our STEM instructional reforms share some similarities with the reform effort described in the Wieman et al. *Change* article from 2010, there is a crucial difference: Our change is led by a bottom-up, small group of faculty members (the CoP), while in their model, change is led by departmental administration. We believe our approach is faster and more efficient. By starting with a small group of like-minded faculty and teaching professionals, significant progress can be made relatively quickly without relying on departmental consensus, which might take longer to reach.

"Teach the Way You Do Research"

It is ironic that although scientists and engineers are quite adept at forging research collaborations, they do not follow similar models in planning and implementing instructional reforms. We found that our motto of "teach the way you do research" resonates among our research colleagues and serves as a litmus test to judge reform strategies: Have the reformers reviewed the literature? What is the research evidence that a particular reform has worked in other settings? What data will be collected both before and after the reform is implemented to judge its effectiveness? Too often reforms are led by individuals based on hunches or personal experience of what works well in their classroom without collecting or analyzing data to explore effectiveness.

Our experience leads us to make the following recommendations for those attempting institutional change:

- Bottom-up instructional reform is a successful model when the department administration is supportive (or at least not in opposition). By starting with a small group of like-minded faculty and teaching professionals, significant progress can be made without the need of departmental consensus.
- Focus reform on specific courses, with faculty members and the department (via the faculty reforming those courses) "owning" the courses, so that faculty rotating into these courses continue to implement the reforms. This supports sustainability.
- Use mentors that help guide the reforms (either faculty, as used here, or postdocs, as used in Wieman et al 2010). Mentors play a crucial role in spreading reform among departments.
- Provide some financial support to initiate CoPs. Although funding can serve as a catalyst for implementing evidence-based instruction, we did not find that the funding *level* was crucial for instructional reform. C

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