Theoretical Perspectives on Change in STEM Higher Education and their Implications for Engineering Education Research and Practice

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**Abstract**

**Background** – Prior efforts have built a substantial knowledge base and a number of effective undergraduate STEM pedagogies, yet rates of implementation remain low. Higher education change processes are at least as complex as the pedagogies and learning processes they seek to promote. The STEM education community is just beginning to view change as a scholarly endeavor informed by the research literature. Theories from higher education, management, communication, and other fields can inform change efforts but remain largely inaccessible to STEM education leaders.

**Purpose** – Our purpose is to describe selected theoretical perspectives on change strategies with potential relevance to STEM higher education settings. The target audience is STEM education change agents, leaders and researchers.

**Scope/Method** – The organizing schema for this review is the four categories of change strategies developed by Henderson, Beach and Finkelstein (2011). Eight strategies of potential practical relevance to STEM education change efforts (two from each category) are described. For each change strategy, we present a summary with key references, discuss their potential applicability to STEM higher education, and discuss implications for change efforts and research on change. We also provide a STEM education example for each strategy.

**Conclusions** – There is evidence that change agents are guided, often implicitly, by a single change strategy. These eight strategies in four categories will expand the repertoire of change agents by helping them consider change from a greater diversity of perspectives. Coordinated work using multiple strategies is more likely to result in the desired transformational change in undergraduate STEM than the limited range currently in use.
Introduction

Increasingly, high profile organizations including ASEE (American Society for Engineering Education (ASEE), 2009), the U.S. National Academy of Engineering (Committee on Science Engineering and Public Policy, 2010; 2004, 2005), Association of American Universities (2011), National Research Council (Committee on Science Engineering and Public Policy, 2006; National Research Council, 2003a, 2003b), and the National Science Board (1986, 2010) are calling for widespread improvements in undergraduate science, technology, engineering and math (STEM) education. This is frequently framed in terms of increasing the number, diversity, and quality of STEM graduates (ASEE, 2009; ASEE, 2012; Hawwash, 2007; King, 2008; National Academy of Engineering, 2004; President’s Council of Advisors on Science and Technology [PCAST], 2012). While these broad goals are not new, growing attention is being paid to the instructional practices of STEM faculty members, specifically to encourage more widespread use of instructional strategies grounded in the research on how students learn (National Research Council, 2012).

Tremendous investment and related efforts over the past few decades have built up a substantial knowledge base about STEM learning and many effective pedagogies and interventions (Borrego, Froyd, & Hall, 2010; National Research Council, 2012; Prince & Felder, 2006). Yet these prestigious groups are increasingly expressing dissatisfaction with the rate of implementation, adoption and scale-up of research-based instructional strategies (ASEE, 2009; ASEE, 2012; National Research Council, 2012; PCAST, 2012). It has become painfully clear that higher education change processes are at least as complex as the pedagogies and learning processes they seek to promote. The STEM education community is just beginning to view change as a scholarly endeavor that can and should be informed by the research literature. While
fields such as management, higher education and communication have developed a wealth of theories to inform such change efforts, they remain largely inaccessible to STEM education leaders and researchers.

The purpose of this research review is to describe selected theoretical perspectives on change strategies and demonstrate their potential relevance to STEM higher education settings. The target audience is STEM education change agents, leaders and researchers. The organizing schema for this paper is the four categories of change strategies developed by Henderson, Beach and Finkelstein (2011; 2010). This is not meant to be an exhaustive literature review of change strategies, but rather is meant to highlight and provide an overview of what we see as some important perspectives on change. Two strategies were selected to illustrate each category of change strategy, and we present a STEM education example for each. These selections were made based on our perception of the current or potential use of each strategy as well as our desire to have the two strategies represent significantly different ways of operating within each category. The discussion and conclusion focus on implications for change agents and future directions for research.

**Theory in Engineering and STEM Education Research**

There are two primary reasons a review of change strategies in STEM higher education is needed. First, change is not traditionally a domain that the STEM community has thought of as informed by theory or literature. The relevant literature on change in higher education is not necessarily accessible to those who need to apply it. This literature is scattered in disciplines and journals outside STEM, and many ideas, although promising, are understudied in the higher education context. Additionally, work being done in instructional change in one STEM discipline
is not necessarily connected to similar work in other STEM education disciplines. Chapter 8 of the Discipline-Based Educational Research (DBER) report calls for more research into the extent to which educational research has influenced undergraduate instructional practices within and across STEM disciplines (National Research Council, 2012).

Second, engineering educators and engineering education researchers have limited experience with education and social science theories. Descriptions of theory use in the DBER report imply that engineering lags far behind physics and chemistry education in its engagement with learning theory (National Research Council, 2012). Engineering education scholars (Beddoes & Borrego, 2011; Borrego, 2007; Koro-Ljungberg & Douglas, 2008) have called for more explicit use of theory in educational research, yet there are few detailed discussions in the engineering education literature about what theory means and how it is best applied in engineering education research and practice.

In the education literature, Creswell (2009) defines theory in quantitative educational research as “an interrelated set of constructs (or variables) formed into propositions, or hypotheses, that specify the relationship among variables (typically in terms of magnitude or direction)…it helps to explain (or predict) phenomena that occur in the world” (p. 51). Using theory to inform interventions and investigations helps us focus on the most important factors to effect the desired changes, whether they are related to student learning or faculty instructional change. Theory helps link the results of an otherwise isolated study to a broader body of research: “Theoretically grounded work connects researchers, allows generalizations across studies, and advances the field of engineering education by avoiding re-inventing the wheel” (Beddoes & Borrego, 2011, p. 283). Thus, linking change efforts to existing theory ensures that new initiatives are informed by and build upon prior efforts. The pressing economic and
environmental challenges facing the world and the need to prepare engineers to meet these challenges means we simply cannot afford to rediscover key aspects of change with each new initiative.

**Change Theories**

The higher education community has been considering questions of how to change faculty instructional practices for decades, and researchers have attempted to make sense of the literature on instructional change for nearly as long (e.g., Emerson & Mosteller, 2000; Levinson-Rose & Menges, 1981; Weimer & Lenze, 1997). Contributing to the complexity is the variety of levels of focus, including individual instructors, departments, institutions and broader education systems. More recent summaries and reviews attempt to capture the complex higher education change processes that bridge individual and organizational scales (Amundsen & Wilson, 2012; Henderson et al., 2011; Kezar, 2001; Seymour, 2002; Stes, Min-Leliveld, Gijbels, & Van Petegem, 2010). While these reviews have helped to situate different perspectives on change with respect to each other and identify the blind spots of a particular approach, the field has not yet developed a coherent understanding of what perspectives are most effective in a given set of circumstances. These reviews tell us that there are many perspectives and approaches to change, which focus on certain aspects of complex higher education systems. We know that certain approaches are a better fit for certain situations, but we do not have a systematic way of thinking about which change perspectives are most appropriate in a given situation. Our review does not attempt to solve this problem; rather, we are describing (comparing, contrasting) different approaches as they apply specifically to engineering and STEM education. To frame this discussion, we employ a framework developed by an interdisciplinary team including physics
education researchers who explicitly focused their analysis on change in STEM undergraduate education (Henderson et al., 2011; Henderson et al., 2010).

**Four Categories of Change Strategies**

Based on a literature review of 191 journal articles published between 1995 and 2008, Henderson et al. (2011; 2010) identified four categories of change strategies that have been used to conceptualize or to create change in undergraduate STEM instruction. The similarity of these categories to those developed through an independent review of an overlapping literature base (Amundsen & Wilson, 2012) suggests that the four categories are robust and meaningful. The four categories, shown in Figure 1, are based on two categorization criteria.

The first criterion focuses on the aspect of the system that is to be changed, ranging from individual instructors to environments and structures. Our use of the terms instructor and faculty throughout this paper is meant to be inclusive of instructors at all levels, including temporary and part-time instructors and tenure-track and tenured professors. However, some of the groups that have applied these strategies have focused on the pressures and reward systems for tenured and tenure-track faculty members.

The second criterion focuses on whether the intended outcome of the change strategy is known in advance, that is, whether the result of the change process is prescribed or emergent. For example, using a specific set of curricular materials, textbook, technology (“clicker” personal response systems), or assessment tool is a prescribed outcome.

Figure 1 clarifies the role of the change agent in each of the four categories. However, it may aid readers’ understanding to know that in Henderson, et al.’s preliminary analysis (2008), they found that each category corresponded to a different community of professionals and their publishing venues. The Disseminating Curriculum and Pedagogy category was dominated by
STEM instructors including DBER scholars. Most of the Developing Reflective Teachers publications were written by faculty developers (i.e., teaching and learning center staff). Most Enacting Policy was reflective of higher education researchers, and the few Developing Shared Vision publications were authored by administrators describing their practices.

<table>
<thead>
<tr>
<th>Aspect of System to be Changed</th>
<th>I. Disseminating: CURRICULUM &amp; PEDAGOGY</th>
<th>II. Developing: REFLECTIVE TEACHERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change Agent Role:</td>
<td>Tell/Teach individuals about new teaching conceptions and/or practices and encourage their use.</td>
<td>Encourage/Support individuals to develop new teaching conceptions and/or practices.</td>
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<tr>
<td>Diffusion</td>
<td>Scholarly Teaching</td>
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<td>Implementation</td>
<td>Faculty Learning Communities</td>
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<th>III. Enacting: POLICY</th>
<th>IV. Developing: SHARED VISION</th>
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<td>Change Agent Role:</td>
<td>Change Agent Role:</td>
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<td>Enact new</td>
<td>Empower/Support stakeholders to collectively develop new environmental features that encourage new teaching conceptions and/or practices.</td>
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<td>environmental features that Require/Encourage new teaching conceptions and/or practices.</td>
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<td>Quality Assurance</td>
<td>Learning Organizations</td>
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<td>Organizational</td>
<td>Complexity leadership</td>
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<td>Development</td>
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**Figure 1.** Change theories mapped to four categories of change strategies. Figure adapted from Henderson et al. (2011). The italicized text in each box lists the eight change strategies discussed in further detail in the text.

In the sections that follow, we discuss two change strategies in each of the four categories (eight total). Summary information for each strategy is provided in Table 1. For each change strategy, we present a summary with key references, discuss their potential applicability to
STEM higher education, and discuss implications for change efforts and engineering education research on change. Then we provide an example of how the strategy has been applied in STEM higher education.
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<tr>
<th>Change Strategy (Fig. 1 Category)</th>
<th>Summary</th>
<th>Key Metaphor</th>
<th>Key Change Agent Role</th>
<th>Key Change Mechanism</th>
<th>Typical Metrics of Success</th>
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<tbody>
<tr>
<td>Diffusion (I. Disseminating Curriculum &amp; Pedagogy)</td>
<td>Innovations are created in one location, then adopted or adapted by others. Multi-stage adoption process.</td>
<td>Scattering</td>
<td>Develop a quality innovation and spread the word.</td>
<td>Adoption decisions by potential users.</td>
<td>Number of users or amount of influence of the innovation</td>
</tr>
<tr>
<td>Implementation (I. Disseminating Curriculum &amp; Pedagogy)</td>
<td>A set of purposeful activities are designed to put proven innovations into practice in a new setting.</td>
<td>Training</td>
<td>Develop a training program that involves performance evaluation and feedback.</td>
<td>Training of potential users.</td>
<td>Fidelity of use of innovation</td>
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<tr>
<td>Scholarly Teaching (II. Developing Reflective Teachers)</td>
<td>Individual faculty reflect critically on their teaching in an effort to improve.</td>
<td>Self-Reflection</td>
<td>Encourage faculty to reflect on and collect data related to their teaching.</td>
<td>Evidence-based reflection on practice.</td>
<td>Self-reported changes in beliefs, teaching practices, or satisfaction with student learning</td>
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<tr>
<td>Faculty Learning Communities (II. Developing Reflective Teachers)</td>
<td>A group of faculty supports each other in improving teaching.</td>
<td>Community Development</td>
<td>Bring faculty together and scaffold community development.</td>
<td>Peer support / accountability, Exposure to new views about teaching and learning.</td>
<td>Self-reported changes in beliefs, teaching practices, or satisfaction with student learning; motivation towards teaching</td>
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<tr>
<td>Quality Assurance (III. Enacting Policy)</td>
<td>Measurable target outcomes are identified and progress towards them is assessed and tracked.</td>
<td>Accreditation</td>
<td>Develop measurable outcomes, define success, collect evidence.</td>
<td>Pressure to meet outcomes.</td>
<td>Degree to which outcome measures are met</td>
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<tr>
<td>Organizational Development (III. Enacting Policy)</td>
<td>Leader develops new vision and plans a strategy for aligning employee attitudes and behaviors with this vision.</td>
<td>Leadership</td>
<td>Develop new vision. Analyze alignment of parts of the organization with the new vision and identify strategy for creating alignment.</td>
<td>Strategic work by the leader to communicate vision and need for change and to develop structures to motivate employees to work towards it.</td>
<td>Productivity-related metrics (e.g., credit hour production, graduation rates, etc.)</td>
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<td>Learning Organizations (IV. Developing Shared Vision)</td>
<td>Leader works to develop an organizational culture that supports knowledge creation.</td>
<td>Team Learning</td>
<td>Move decision-making further from the top. Invest in developing employees personal mastery, mental models, shared vision, team learning.</td>
<td>Team-level questioning and revision of mental models (i.e., double loop learning: Argyris and Schon, 1974) facilitated by middle managers.</td>
<td>Vague and situation dependent</td>
</tr>
<tr>
<td>Complexity Leadership (IV. Developing Shared Vision)</td>
<td>In a complex system, results of actions are not easily predicted. Change agents can create organizational conditions that increase the likelihood of productive change.</td>
<td>Emergence</td>
<td>Disrupt existing patterns, encourage novelty, and act as sensemakers.</td>
<td>New ideas emerge through interactions of individuals. Formal leaders encourage this process by creating disequilibrium and amplifying productive innovations.</td>
<td>Vague and situation dependent</td>
</tr>
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</table>
Underlying Logic of Change Strategies

A useful frame for our discussion of change strategies is a concept from the field of evaluation: logic models. In evaluation, a logic model is a detailed map developed to clarify and communicate goals, intermediate outcomes, and measures for a specific project (W.K. Kellogg Foundation, 2004). Logic models make explicit which actions are intended to cause desired changes (McLaughlin & Jordan, 1999). Logic models are closely related to theories of action and theories of change (Center for Civic Partnerships, 2007; Milstein & Chapel, N.D.), all of which emphasize their focus on communicating the logic and assumptions underlying a change effort. Logic models and theories of change can be quite extensive, including full-page or larger maps connecting boxes of activities, outcomes, stakeholders and indicators (Keystone, 2009; W.K. Kellogg Foundation, 2004). Since we are describing general strategies and not specific programs or projects, we cannot present full logic models. However, inspired by this concept, we articulate the underlying logic for each of the change strategies described in this article, summarized in a sentence or two, supplemented by the more detailed description of the approach and its limitations and assumptions. We hope this encourages others to be more explicit in their change logic as well.

Choosing the “Right” Theory

Readers might wonder how to use this information comparing a range of change strategies. Our advice for those embarking on a change effort is to select the one strategy and underlying theory that fits the situation best (in terms of goals, locus of change, and implicit assumptions about change already in play). Readers should consider it as a design problem: within the constraints, some options fit better than others, but there is no clear right or wrong answer. For example, when studying effectiveness of dissemination efforts, a dissemination
framework is most likely to identify productive variables and processes on which to focus. In publications, part of the peer review process is evaluating the appropriateness of the theoretical framework. Our goal in writing this article is to clarify the goals, assumptions, and underlying logic of each strategy so that readers can pick the one that fits their situation best (and later, articulate it in their own writing).

At the end of this article we suggest that multiple change strategies will increase the likelihood of success. However, STEM education change agents are unaccustomed to discussing their work in terms of change theories or the categories of strategies presented here. In our experience, there is a tendency to overestimate the novelty and reach of change initiatives, for example, claiming a fundamentally new, far-reaching approach that in actuality fits squarely into one of the established categories in Figure 1. Therefore, we suggest that STEM higher education change agents focus on applying and communicating one primary strategy before attempting to employ multiple strategies.

Category I: Disseminating Curriculum and Pedagogy

Change strategies in this category focus on changing individuals (typically faculty members) in a prescribed way. Henderson et al. (2011) found that within the STEM undergraduate education research community, strategies in this category are the most commonly used and discussed. In fact, discussions about how to improve undergraduate STEM instruction are typically conceptualized solely within this category. Working from the assumption that faculty have limited time and expertise to develop improved teaching methods, STEM change agents develop and perfect highly structured and specific interventions to be easily implemented by others. This is the basic change model behind many change initiatives in undergraduate STEM (Seymour, 2001) and also the change model implicit in influential funding programs for
undergraduate STEM educational improvement, such as the NSF Transforming Undergraduate Education in STEM (TUES), and its predecessor, Course, Curriculum and Laboratory Improvement (CCLI). These ideas are elaborated below in specific descriptions and examples of diffusion and implementation.

**Diffusion**

**Underlying logic.** The STEM undergraduate education system will be changed by changing the behavior of a large number of individual instructors. The greatest influences for this lie in optimizing characteristics of the innovation and exploiting the characteristics of individuals and their networks.

**Description.** The term “Diffusion of Innovations” was popularized by a book of the same name first published by Everett Rogers in 1962 and now in its 5th edition (Rogers, 2003). The theory has been used to describe adoption of a wide range of innovations, including agricultural equipment, public health interventions, and cellular telephones, and has demonstrated relevance to diffusion of instructional strategies. Three features of Rogers’ theory are often implicit in discussions about STEM education change initiatives. First, much of diffusion of innovation theory focuses on the characteristics of the innovation (i.e., an instructional strategy or curricular approach), for example, how much better the innovation is than current practice (relative advantage) and how hard it is to understand and use the innovation (complexity). The second feature is that adoption is conceptualized as an individual choice. Potential adopters (faculty members) are often categorized in terms of their ‘innovativeness’ (e.g., whether they are innovators, early adopters, early majority, late majority, or laggards), and this information may be used to target influential leaders or individualize dissemination strategies by adopter type. Finally, once enough people adopt an innovation (Rogers suggests between 10 and 25%), it will
reach a critical mass (or tipping point (Gladwell, 2000)), after which the innovation will continue to spread on its own until it saturates the system.

Another important aspect of Rogers’ view of diffusion of innovations is the depiction of adoption decisions as a series of stages. Adopters do not move from knowing nothing about an innovation to adopting it in one step. While there are many different descriptions of the stages through which an adapter reaches the point of using an innovation, the five-stage description offered by Rogers (2003) provides a useful framework:

1. Awareness—Awareness of the innovation, but lacking complete information about it.
2. Interest—Growing interest and information seeking.
3. Evaluation—Decision whether or not to try innovation based on present and future situation.
4. Trial—Making use of the innovation.
5. Adoption—Continued use of the innovation.

Research in multiple STEM disciplines (Borrego et al., 2010; Froyd, Borrego, Cutler, Henderson, & Prince, in press; Henderson, Dancy, & Niewiadomska-Bugaj, 2012; Prince, Borrego, Henderson, Cutler, & Froyd, in press) suggests that strategies currently used by change agents have been relatively successful at creating awareness and interest but have not been as successful at supporting faculty during the trail stage, thus leading many faculty to discontinue use or to modify the innovation in ways that likely diminish its effectiveness. Diffusion of innovations is a robust theory that allows for some influence from the system, lots of adaptation, phased adoption, and many other aspects of change. Many of the limitations arise because STEM education change agents have not paid attention to all of the important aspects of a diffusion perspective in their change efforts or they have attempted to apply a diffusion
perspective in situations where it is not appropriate. For example, instructional strategies that rely on computer programs have not always been designed for others to easily adapt them to local conditions.

Building on the work of Rogers and many others, Wejnert (2002) provides a very useful framework of 3 categories of variables associated with diffusion of innovations (Table 2). We note that many of the variables identified by Wejnert have not yet been studied in a higher education context; however, they should provide guidance to researchers and change agents in developing a change initiative. One important aspect of change that is beginning to be articulated by STEM education researchers is related to the variable of position in social networks. While many STEM-based change agents have tended to think of diffusion as a process that occurs by a developer using mass-marketed distribution methods (e.g., publishing articles, giving talks), mounting evidence suggests that the most successful diffusion occurs through personal interactions between individuals or in small groups (e.g., Dancy, Turpen, & Henderson, 2010; Prince et al., in press). These personal interactions occur, for example, during informal conversations with colleagues or when instructors were trained as graduate teaching assistants early in their careers. Although STEM education dissemination efforts have in recent years been focused at a national or international level, this theory helps explain the importance of local communities and networks that STEM education leaders are increasingly noticing.
Table 2. Conceptual framework of diffusion variables. From Wejnert (2002).

1. Characteristics of Innovations
   - Public versus private consequences
   - Benefits versus costs
2. Characteristics of innovators
   - Societal entity
   - Familiarity with the innovation
   - Status characteristics
   - Socioeconomic characteristics
   - Position in social networks
   - Personal characteristics
3. Environmental context
   - Geographical settings
   - Societal culture
   - Political conditions
   - Global uniformity

Diffusion example. Montfort, Brown and Pegg (2012) used diffusion of innovations theory to study adoption of an assessment instrument designed for use in capstone design courses. The team conducted interviews with developers of the instrument, current users, and educators who attended workshops to learn about the instrument. The authors used stages of adoption (knowledge, persuasion, passive rejection, decision, implementation, active rejection and confirmation) to describe the participants and contextualize their responses. The authors compared participants’ perceptions of the instrument in terms of compatibility with their teaching approaches and environment, relative advantage over current approaches, and complexity. They found that compatibility was the only useful construct that consistently explained adoption decisions. For example, if study participants were not using the instrument, it was because they did not feel it was compatible with the capstone design course in their department (and alternatively, those who were using it thought it was compatible with how the course is run). While the compatibility explanation was consistent, different participants described the same features of the instrument as positive or negative, depending on their
perspective and local environment. The authors also explored the role of communication channels and found that, consistent with predictions from diffusion of innovation, interpersonal channels (word of mouth) were more effective than “mass media” (workshops). However, they also suggested that future work needs to more carefully consider how the wide variety of communication modes from the theory applied to engineering education. Finally, the authors noted limitations of the individualized focus of diffusion theory because the capstone design setting is often coordinated by a team of instructors and assessment specialists who must agree on adoption decisions.

Implementation

**Underlying logic.** The STEM undergraduate system will be changed by developing research-based instructional ‘best practices’ and training instructors to use them. Instructors must use these with fidelity.

**Description.** An important distinction between diffusion and implementation is the level of deliberateness that lies behind an implementation strategy. While diffusion-based strategies are characterized by developing good products and spreading the word about them, implementation-based strategies are characterized by the focus on carefully developing a set of activities designed to put the innovation into successful practice in a new setting. Although implementation strategies are not yet widely used for higher education curricular innovations, these strategies have been used extensively in K-12 settings (Cooper, 2008). Fixsen et al. (2005) describe implementation in terms of five components (see Figure 2). The process is driven by a proven educational product or practice (the source) that the change agent seeks to have adopted by instructors (the destination). The change agent identifies current practices of the destination instructors and sphere of influence surrounding the destination instructor (e.g., the cultures and
structures in destination departments) and provides appropriate training and coaching (the communication link) to the destination instructor. Progress is measured by documenting knowledge and use of the new practice by target instructor. This is the approach increasingly being advocated by the U.S. National Science Foundation’s TUES program, for example through encouraging projects that “promote widespread implementation of educational innovations” (Feser, Borrego, Pimmel, & Della-Piana, 2012; National Science Foundation, 2010, p. 4).

Figure 2. A conceptual view of implementation. Adapted from Fixsen et al. (2005).

Based on a review of implementation literature in a variety of fields, Fixsen and coworkers found that implementation efforts are most successful when the core components of the source program or practice are known and clearly defined (2005). One study in engineering education focused on defining these “critical components” and advocating for more attention to implementation (Author, in press). Performance evaluation and feedback are crucial in supporting successful use of the core components (Fixsen et al., 2005; Henderson et al., 2011). In implementation, there is a strong emphasis on communication and feedback that connects the source practice (new instructional method) to the destination (implementing faculty). As Fixsen et al.(2005) summarize as a primary finding of their literature review, “information
dissemination alone is an ineffective implementation method” (p. 70). This suggests that undergraduate STEM education change agents should pay more attention to feedback from users during dissemination.

**Implementation example.** Gallos, Van den Berg, and Treagust (2005) describe the use of an implementation approach to the improvement of instruction in a general chemistry course. Once a new instructional style was developed and pilot tested, 13 instructors who taught the course were enrolled in a training program. The training program began the semester prior to implementation. The instructors observed the pilot version of the revised course and attended weekly training sessions. During the training sessions, the instructors learned about the philosophy behind the new course and were engaged in refining curricular materials to fit with the new philosophy. During the implementation semester, the 13 instructors met with the developer in weekly small group sessions to discuss implementation issues. The developer and another pedagogical expert regularly observed lessons and provided feedback and assistance to the instructors. Metrics related to implementation of the new instructional style were developed and used to assess the fidelity of the implementation. One metric was the number of minutes in each class session that were used for instructor lecture, seatwork, and closure/summary. Another metric used was a checklist of variables related to the seatwork portion of the class, for example, whether the instructor assigns seatwork to individuals or pairs, or whether the instructor moves around the classroom. Based on these metrics, the authors concluded that 9 of the 13 instructors were successful in changing their instruction.

**Disseminating Curriculum & Pedagogy (Category I) Summary**

Change strategies within the disseminating curriculum and pedagogy category all rely on having a ‘thing’ (i.e., an instructional strategy or teaching materials) to disseminate. Defining
this ‘thing’ and the range of acceptable variation is an important step in any change strategy in this category.

Within this category, diffusion and implementation represent two different emphases that could be successfully combined. The emphasis in diffusion is on developing a good product and letting potential users know about it, perhaps by targeting influential opinion leaders. STEM education research indicates that diffusion strategies have been successful at the early awareness stages, but cater less to instructors who need to understand the details of implementation. An implementation approach is much more focused on supporting the potential user through the entire process. Like diffusion, an implementation perspective requires a communicating to potential users the compatibility and relative advantage of the innovation. Unlike diffusion, the emphasis in implementation is on providing the user with appropriate monitoring, feedback, and support during the implementation process. Thus, combining these two perspectives would be possible and productive by emphasizing diffusion at early stages to raise awareness and convince instructors to try the strategies and implementation at later stages to support users in ongoing use.

Category II: Developing Reflective Teachers

This category develops instructors as reflective practitioners (Brookfield, 1995; Schön, 1983, 1987; Zeichner & Liston, 1987; Zeichner & Noffke, 2001). The focus is on instructors as individuals or part of a community, and the outcome is emergent. Emphasis is on engaging and empowering faculty members to reflect on their teaching practice, frequently through consideration of assessment evidence, to make instructional changes based on their best judgment. The process is often informed by the education research literature (Mettetal, 2001), and this evidence often also directs faculty to use (or independently develop) research-based instructional strategies. This is the approach most frequently taken in teaching and learning
centers, which provide consultation services to motivated faculty members, and may sponsor faculty learning communities as well. While not specifically limited to STEM education, these strategies have been applied in programs targeting engineering and STEM instructors.

**Underlying logic.** The STEM undergraduate system will be changed when large numbers of individual faculty members treat their teaching as a scholarly activity.

**Description.** Scholarly teaching is “a method of finding out what works best in your own classroom so that you can improve student learning” which “fits in the center of a continuum ranging from personal reflection at one end to formal educational research at the other” (Mettetal, 2001, p. 1). The major characteristics of scholarly teaching are listed in Table 3. While other sources describe and distinguish scholarly teaching from Scholarship of Teaching and Learning and related approaches (Borrego, 2007; Hutchings & Shulman, 1999; Streveler, Borrego, & Smith, 2007), we discuss them collectively for the purposes of this review.

**Table 3.** Main Characteristics of Scholarly Teaching (Connolly, Bouwma-Gearhart, & Clifford, 2007, p. 22).

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<td>Drawing upon the work of others, including disciplinary colleagues, education researchers, and students;</td>
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<tr>
<td>Posing an explicit question about the effectiveness of one’s practice;</td>
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<tr>
<td>Creating and following an explicit design or plan;</td>
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<tr>
<td>Collecting credible evidence to answer the question;</td>
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<tr>
<td>Analyzing and interpreting evidence;</td>
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<tr>
<td>Reflecting on one’s findings;</td>
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<tr>
<td>Acting on one’s findings;</td>
</tr>
<tr>
<td>Engaging in ongoing and cyclical inquiry;</td>
</tr>
<tr>
<td>Documenting and disseminating processes and outcomes of inquiry; and</td>
</tr>
<tr>
<td>Being principally responsible for conducting the inquiry on one’s own practice;</td>
</tr>
</tbody>
</table>

A number of publications provide advice on developing scholarly teaching among engineering instructors specifically (e.g., Baillie, 2007; Felder, Brent, & Prince, 2011; Kolmos, Vinther, Andersson, Malmi, & Fuglem, 2004). Perhaps the most salient characteristic is that
scholarly teaching emphasizes using data in decision making (Connolly et al., 2007; Mettetal, 2001). Instructors may be initially motivated to improve their teaching, or to create required materials for their dossiers. These projects can create a greater sense of excitement about teaching, and they often prompt teachers to change their teaching (Mettetal, 2001).

The individual nature of this approach is highlighted by practical advice from Mettetal:

Since the goal… is to inform decision-making, the question or problem should look at something under teacher control, such as teaching strategies, student assignments, and classroom activities. The problem should also be an area in which you are willing to change. There is no point in conducting a … project if you have no intention of acting on your findings. Larger institutional questions might be tackled, if the institution is committed to change. (Mettetal, 2001, p. 3)

Additionally, he advises instructors to select a feasible project in a course that is progressing well, and gradually working up to tackling more challenging problems (Mettetal, 2001).

**Scholarly teaching example.** Raubenheimer and Myka (2005) describe using scholarly teaching methods in the improvement of a first-year zoology laboratory course. The faculty member who taught the lab (one of the authors) was dissatisfied with students’ learning and, in collaboration with another faculty member in the education department (the other author), sought to make improvements. The article describes three cycles of applying a research approach to improving the lab. In each cycle, questions were posed, data were collected and analyzed, and changes were made in instruction. The article describes very nicely the cyclical inquiry process that is a core feature of scholarly teaching. As exemplified in the article, one of the core reasons that scholarly teaching is so powerful is that each cycle leads the instructor to ask more sophisticated questions and collect different types of data to answer the questions.
Faculty Learning Communities

**Underlying logic.** The STEM undergraduate system will be changed by groups of instructors supporting and sustaining each other's interest, learning, and reflection on their teaching.

**Description.** While scholarly teaching is primarily a solitary endeavor, faculty learning communities seek to create a support network around similar ideas of using evidence to improve teaching. Cox defines faculty learning communities as a type of community of practice,

> a cross-disciplinary faculty and staff group of six to fifteen members… who engage in an active, collaborative, yearlong program with a curriculum about enhancing teaching and learning and with frequent seminars and activities that provide learning, development, the scholarship of teaching, and community building. (2004, p. 8)

Faculty learning community participants are expected to select a target course to try out new and innovative teaching approaches and then assess resulting student learning (e.g., as described in Calkins & Light, 2007; Lynd-Balta, Erklenz-Watts, Freeman, & Westbay, 2006). Evidence shows that faculty learning communities increase instructor interest in teaching and learning and provide safety and support for instructors to change longstanding instructional practices (Beach & Cox, 2005). The ultimate goal of instructor participation in faculty learning communities is improved student learning; however, it is common for participants to engage in action research in their courses and present project results at local, regional, and national conferences and in disciplinary journals.

Faculty learning communities address the weaknesses of traditional professional development approaches by providing a long-term collaborative structure of safety and support for instructors to investigate, attempt, assess, and adopt teaching methods that are new to them (Beach & Cox, 2005; Cox, 2004). They allow for individual instructors to choose the approaches most interesting to them, help instructors through the “implementation dip,” and
assume that instructors want and need to adapt teaching approach to their unique courses. Some specific implementations of faculty learning communities are described in (Erklenz-Watts, Westbay, & Lynd-Balta, 2006; Fleming, Shire, Jones, Pill, & McNamee, 2004; Scott & Weeks, 1996; Wildman, Hable, Preston, & Magliaro, 2000). The faculty learning community implemented by Lynd-Balta et al. (2006) included primarily science faculty and found that most of the members had made or planned to make significant changes in their teaching.

Participation in a faculty learning community increases awareness of different teaching and learning styles and broadens awareness of different cultures and disciplines. It engages and empowers instructors to make changes, potentially at the curriculum level, through collaboration. In fact, it may have some overlap with next category, learning organizations, because all members of the group are learners, and the organization is structured to learn as a whole system (Cox, 2004). Finally, faculty learning communities have positive outcomes for faculty retention (Cox, 2004).

**Faculty learning communities example.** Lynd-Balta et al. (2006) describe a year-long faculty learning community in which an interdisciplinary group of eight faculty met monthly for three-hour evening sessions. Each of the participants was interested in working to improve their teaching to better develop students’ critical thinking skills. The group was facilitated by the first two authors, one from the biology faculty and one from the education faculty. The learning community was developed to introduce participants to some important results from education research and to allow them to reflect and discuss how the ideas apply to their courses. Each participant was expected to focus on a particular instructional unit that they wished to improve. These units were implemented near the end of the faculty learning community year, and results were reported to the group. Participants identified the structured reflection and peer support of
the learning community as important contributors to their ability to make significant changes to their instruction.

**Developing Reflective Teachers (Category II) Summary**

A major advantage of strategies within the developing reflective teachers category is that they help to support instructors in changing aspects of instruction that the instructors are interested in changing. The support and encouragement often offered to instructors within these strategies helps to promote productive outcomes and, in particular, helps to avoid discontinuation which can occur during the risky trial period when new instructional approaches are first being implemented. The major strength of these strategies as being strongly instructor-driven is also the major weakness of these strategies. This approach does little to involve resistant faculty members. It is focused and dependent on faculty motivation to a greater extent than the other approaches, and it is clearly a bottom-up approach to change.

**Category III: Enacting Policy**

We now shift from strategies directly targeting individuals to strategies targeting the environments in which individuals work. This category emphasizes guiding organizations (and the people within them) towards a prescriptive goal. In this setting, the goal would be improved teaching and/or increased use of research-based instructional strategies, although much of the literature is written independent of the specific goal (as it assumes leaders have one in mind). With the exception of the prevalence of accreditation systems governed by organizations such as ABET (U.S.-based accreditation organization) and Engineers Australia, these strategies have generally not been applied as change strategies in undergraduate STEM education.
Quality Assurance

**Underlying logic.** The STEM undergraduate system will be changed by requiring institutions (colleges, schools, departments and degree programs) to collect evidence demonstrating their success in undergraduate education. What gets measured is what gets improved (Steering Committee for Evaluating Instructional Scholarship in Engineering, 2009).

**Description.** Quality assurance is a process by which organizations collect and analyze their own evidence to evaluate and improve their ability to meet stated goals. In higher education, the process has evolved to include the major steps of: setting goals or targets, preparing a self-study report with evaluation evidence, hosting an external visit by peers, and responding to the external review report (Ewell, 1997; Rhoades & Sporn, 2002). Quality assurance is becoming increasingly popular in institutions and engineering programs around the world. The dominant example of quality assurance in the U.S. (and increasingly in other countries) is ABET accreditation of degree programs. In Australia, the Institute of Engineers coordinates a nearly identical process. Quality assurance in European engineering education is focused on the Bologna process for promoting “convergence and transparency in qualification structures in Europe” (De Wit, 2000, p. 9) aligning engineering programs to encourage mobility of graduates. There are also regional or national accreditation organizations which focus at the institution level, across all disciplines. However, engineering accreditation systems have generally been ahead of regional systems, for example, in requiring outcomes-based accreditation a few years before regional accreditation agencies in the U.S. These higher and/or earlier standards of engineering accreditation systems are one important reason engineering education leaders tend to focus on ABET and similar systems in their discussions of quality assurance.
Quality assurance is linked with many management trends from industry, including strategic planning (Rhoades & Sporn, 2002). These trends jump sectors from industry to higher education through people who bridge them, such as industrial advisory board members (Birnbaum, 2000; Rhoades & Sporn, 2002), which might explain why engineering education quality assurance through ABET accreditation is more developed than regional accreditation activities in U.S.

In general, as Rhoades and Sporn explain, “Quality assurance in the U.S. has never been taken to mean a high standard of comparable quality across institutions,” because accreditation associations “have focused on ensuring a minimum level of competence” (2002, p. 376). Thus, quality assurance operates more at the trailing edge of change efforts rather than the leading edge. The rate of changes effected by quality assurance can seem painfully slow, but they ensure that all participating institutions meet a minimum level of compliance. Therefore, quality assurance is less useful as a leading-edge change strategy than it is helpful in bringing a large number of programs up to a new standard.

Finally, we note the issues related to the types of evidence used in quality assurance and accreditation. Quality assurance is increasingly linked to internal and external resource allocation, which is beginning to lead to emphasis on productivity and focus on outcomes that are easy to measure (Rhoades & Sporn, 2002). However, aspects of learning that are easy to measure or have been traditionally measured are not necessarily the best evidence. Teaching evaluations are one source of evidence prevalent in the U.S., where they have been used since the 1970s and at a rate of up to 95% adoption (Cashin, 1999; Rhoades & Sporn, 2002). Yet many argue that these are indirect and invalid measures of teaching effectiveness (Greenwald, 1997; Kulik, 2001). Fortunately, these are not widely used in learning/program assessment and
accreditation; however, they are typically an important data source considered in promotion and tenure decisions for faculty members. As stakes are raised, we need to ensure that measures align to desired outcomes.

**Quality assurance example.** Over the course of a multi-year transition beginning in 1996, ABET implemented new EC2000 outcomes-based assessment criteria, a significant departure from the previous system focusing on hours of instruction in various subjects (Prados, Peterson, & Lattuca, 2005). This spurred countless administrators and faculty members who had survived an accreditation visit to share their experience, advice, and assessment systems through publications, most commonly at the Frontiers in Education conference (www.fie-conference.org). In *Journal of Engineering Education*, Georgia Tech Engineering Associate Dean for Academic Affairs Jack Lohmann (1999) described the process of engaging engineering faculty members in development of mission/vision statements, outcomes and objectives, and systems for collecting and using assessment data. He offers the following advice for others preparing for their first accreditation visit under the new criteria:

1. Focus on what is important to your College first; focus on what is important for accreditation second.
2. Improve existing assessment processes and measures first.
3. Share information and collaborate as much as possible.
4. Clarify terminology and establish the key elements of the assessment plans early in the development process.
5. Identify benchmark institutions and key constituents.
6. Gather data, and lots of it.
7. Develop a system to document the use of results. (pp. 308-309)
A number of other early publications focus on developing learning objectives and outcomes (Felder & Brent, 2003; Scales, Owen, Shiohare, & Leonard, 1998).

ABET is commonly criticized for stifling instructional innovation and improvement in engineering undergraduate education (ASEE, 2009). In fact, the major change to outcomes-based accreditation in 2000 has been cited as having a significant impact on engineering education. Volkwein, et al. (2007) found substantial increases in emphasis on professional skills, active learning and assessment-informed curricular improvements between 1994 and 2004 as a result of ABET’s implementation of EC2000 accreditation criteria. Similarly, Froyd, Wankat and Smith (2012) identified outcomes-based accreditation through ABET as one of “five major shifts in 100 years of engineering education.” However, in the decade since this change, most engineering accreditation activity has become routinized. The path of least resistance for most faculty members and administrators is to keep teaching and documenting student learning the same way from year to year. Changing the way an engineering course is taught, for example to implement more projects or active learning, would require not only the changing the course itself, but also rethinking learning outcomes and documentation. If previous practice resulted in a program being accredited, there is little incentive to change courses or engage in faculty professional development. In this way, program accreditation has become a disincentive to undergraduate instructional change.

Organizational Development

Underlying logic. The STEM undergraduate system will be changed by administrators with strong vision who can develop structures and motivate faculty to adopt improved instructional practices.
Description. Another management trend that has moved into higher education is organizational development and organizational transformation\(^1\), which are “aimed at the planned change of organizational vision [and/or] work settings” (Porras & Silvers, 1991, p. 54). As depicted in Figure 3, planned changes (interventions) in work settings are intended to create cognitive changes in employees, which lead to behavioral changes and improved organizations. Improvement of the organization can mean a better fit between its capabilities and current environment or a predicted future environment (Porras & Silvers, 1991).

Figure 3. Logic model for organization transformation and organization development. Adopted from (Porras & Silvers, 1991).

Although some of the approaches are aimed at individuals and may result in bottom-up change, the overall approach is top-down in the sense that management identifies a mismatch and initiates a planned change effort. However, the interventions comprise both organization-level and individual perspectives (Porras & Silvers, 1991).

\(^1\) Although researchers in this area distinguish between organizational transformation and organizational development, we will combine them for the purposes of this overview.
Kotter presents accessible versions of these approaches in terms of strategies for influencing individuals and organizations at various stages of the change process (1995; Kotter & Schlesinger, 1979). Graham (2012) argues that Kotter’s (1996) stage model of top-down change has been the most influential in engineering education, perhaps because Froyd, Penberthy and Watson (2000) provided an adaptation of the steps to engineering undergraduate education change initiatives, which is listed in Table 4. However, it is difficult to point to publications describing specific engineering or STEM education change efforts that have been guided by this perspective.

**Table 4.** Froyd et al.’s (2000) adaptation of Kotter’s (1996) stage model to engineering education.

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<table>
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<tbody>
<tr>
<td>1. Establish need and energy for a curricular change</td>
<td>(Establish a sense of urgency)</td>
</tr>
<tr>
<td>2. Gather a leadership team to design and promote the curricular change</td>
<td>(Create a guiding coalition)</td>
</tr>
<tr>
<td>3. Define and agree upon new learning objectives and a new learning environment</td>
<td>(Develop a vision and strategy)</td>
</tr>
<tr>
<td>4. Discuss the new objectives and environment with the college and revise based on feedback</td>
<td>(Communicate the change vision)</td>
</tr>
<tr>
<td>5. Implement new curriculum using a pilot, if necessary</td>
<td>(Empower broad-based action)</td>
</tr>
<tr>
<td>6. Conduct a formative evaluation of the program, investigating strengths and weaknesses of the current implementation, and indicators of short-term gains</td>
<td>(Adjust for growing pains and generate short-term wins)</td>
</tr>
<tr>
<td>7. Decide how the new approach may be used for the entire college and prepare an implementation plan</td>
<td>(Consolidate gains and produce more change)</td>
</tr>
<tr>
<td>8. Prepare faculty and staff for the new implementation, implement, and follow up with improvements</td>
<td>(Anchor new approaches in the culture)</td>
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</table>

In general, many of the details require adaptation from an industry setting to higher education, for example, measuring change success in terms of profit or productivity. However, this research does provide some guidance on evaluating the readiness of individuals (Fisher, Merron, & Torbert, 1987; Gardner, Dunham, Cummings, & Pierce, 1987; Piderit, 2000) and organizations (Beer, 1987; Nadler & Tushman, 1989) to undertake change efforts. Porras and
Silvers also present a promising array of quantitative and qualitative methods for evaluating the impact of these types of change efforts (1991).

**Organizational development example.** Ponitz (1997) describes the use of an organizational development strategy in the implementation of learning outcomes at Sinclair Community College. According to Ponitz, in the 1980’s Sinclair’s president felt external pressures to emphasize student performance as a measure of institutional effectiveness. This led the president to develop the vision of a guarantee for the competencies of Sinclair graduates which would ensure that each graduate was ready for the workplace or for transfer to a baccalaureate degree program. According to this policy (approved by the board of trustees) a Sinclair graduate could receive additional free education if they were judged by their employer to not possess a job skill identified as a learning outcome of their degree program.

In support of this vision, the president called for the development of learning outcomes for each program and procedures for documenting that students have met these outcomes. This effort was coordinated by an Assessment Steering Committee which was charged with reviewing current assessment practices at Sinclair and making recommendations for improvement. The committee adopted a set of 12 principles of assessment to guide the assessment initiatives. It then developed several assessment-related policies that were adopted by the board of trustees. For example, one of the policies required all degree programs to have clearly defined learning outcomes, to publish these outcomes, and to identify specific courses that prepare students to achieve each outcome. The Steering Committee reviewed the results of the program annually and made improvements as needed. One of the key mechanisms used to communicate the vision of assessment was the job competency guarantee envisioned by the president and enacted throughout the college.
Category III (Enacting Policy) Summary

This category of change strategies is strongly influenced by management practices in industry. While quality assurance is practiced extensively in higher education and particularly in engineering program accreditation, it is not often cited as an effective change strategy. Quality assurance is better thought of as a long-term, often evolutionary, change process that may have more impact on bringing all programs up to a minimum level of quality. However, as discussed, changes in quality assurance can result in significant changes over time, as has been seen with the ABET criteria. There is also often a synergy between quality assurance and organizational development in that organizational development is often initiated as a result to changes in external circumstances, such as new accreditation criteria. Understanding the underlying assumptions of these strategies (i.e., maintaining a minimum level of quality) helps advocates and change agents understand the limitations and select an appropriate strategy.

It should be emphasized that these strategies are a better fit for a specific change, such as a new curriculum or system for advising or evaluating faculty members. More general efforts directed at changing the culture for supporting teaching improvement might best be handled through a shared vision approach.

Category IV: Developing Shared Vision

Change strategies in the final category, developing shared vision, focus on changing environments and structures to support the development of emergent teaching innovations. Henderson et al. (2011) found that strategies of this type are not widely used or discussed within the STEM education research community or even the broader higher education community. Most of the ideas in this category have been developed within an industry context. Thus, while these ideas seem promising, their applicability is largely untested in higher education.
Learning Organizations

**Underlying logic.** Innovation in the STEM education system will occur through communities of practice in which individuals develop new organizational knowledge through sharing implicit knowledge about their teaching. Leaders cultivate conditions for both formal and informal communities to form and thrive.

**Description.** The idea of learning organizations is popular in the field of management. The core idea is that businesses need to continually learn and improve in order to be successful in the rapidly changing marketplace. There are two essential conditions for a learning organization: 1) new ideas must be developed and, 2) these ideas must lead to changes in the way the organization operates (Dill, 1999). Unlike prior views of an organization, however, in which the management is the ‘brains’ and the line workers simply implement the ideas of management, in a learning organization, the organizational knowledge needed to be successful comes from throughout the organization. The role of management is to foster conditions that support the development of this knowledge. Two seminal books related to this idea are “The Fifth Discipline” (Senge, 1997) and “The Knowledge Creating Company” (Nonaka and Takeuchi, 1995).

A central theme of both books is that individuals’ models about the way the world works (which are often implicit) shape how they perceive and interact with the world. Organizational knowledge is created when individuals attempt to make their mental models explicit and share these models with others in the organization. Middle managers or line managers are typically seen as the interface between the front line workers and the upper levels of the organization that facilitate this knowledge creating process. Nonaka and Takeuchi (1995) call this learning
organization structure as middle-up-down management in order to contrast it with more familiar top-down or bottom-up styles.

Knowledge is created by middle managers, who are often leaders of a team or task force, through a spiral conversion process often involving both the top and the front-line employees (i.e., bottom). The process puts middle managers at the very center of knowledge management, positioning them at the intersection of the vertical and horizontal flows of information within a company. (p. 127)

Senge (2000) suggests that department chairs are the middle managers of higher education and that their important role in a learning organization is “to facilitate ongoing reflection and conversation to identify clear goals and establish agreed-upon strategies to move towards those goals. These strategic conversations link them vertically to those above them in the hierarchy, as well as to those below them.” (p. 285).

The use of department-level collaborative management has been linked with faculty use of more student-centered instruction (Martin, Trigwell, Prosser, & Ramsden, 2003; Ramsden, Prosser, Trigwell, & Martin, 2007). Collaborative management for teaching involves department heads continually engaging faculty in systematic discussions of the student experience in department courses and working collaboratively with faculty to improve these experiences. This type of department-level leadership is uncommon (Martin et al., 2003). Department-based team learning focused on teaching is also sometimes described as analogous to the development of new knowledge by a research team. For example, Marbach-Ad et al. (2007) describe a “research group approach” that was used to develop a sequence of microbiology courses. A small group of faculty members identified instructional goals, searched the literature for relevant instructional methods, developed new instructional methods, and tested and refined these methods. Kerr and Runquist (2005) describe a similar approach using diverse teams of faculty and students in their chemistry curriculum development project. As they note, working as a team, as opposed to a
committee, for example, is not a common work mode in higher education, and team training is important.

**Learning organizations example.** Although the learning organization framework has not applied much in the higher education literature, there is some evidence that higher education institutions can shift their management processes to operate more like learning organizations (Dirckinck-Holmfeld & Lorentsen, 2003; Kezar, 2006). For example Aalborg University (Denmark) used a learning organization perspective to increase the productive incorporation of information technology throughout institutional operations (Dirckinck-Holmfeld & Lorentsen, 2003). Based on this perspective, they organized their initiative around development projects in which small groups would develop new ideas for their local environments. Through increased sharing of ideas between these groups, good ideas would gradually become apparent and then these could be institutionalized. A number of specific mechanisms were used to facilitate the sharing of ideas and resulting organizational learning. For example, to facilitate organizational learning from the development projects, there was a core project group consisting of instructors from across the campus. One of the activities of this group was to regularly visit and learn about specific projects and then work to incorporate productive new ideas into formal organizational policy through participation in various institutional boards.

**Complexity Leadership**

**Underlying logic.** The STEM undergraduate education system is a complex system. *Innovation will occur through the collective action of self-organizing groups within the system. This collective action can be stimulated, but not controlled.*

**Description.** Complexity has been an increasingly productive area of study in both natural and social sciences (e.g., Goldstein, Hazy, & Lichtenstein, 2010). Complex systems
cannot be completely described and, thus, the dynamics of a complex system cannot be completely controlled or predicted. An important phenomenon in complex systems is emergence – the development of new system properties or structures from relatively small and/or routine interactions of system elements. Complexity leadership theory combines ideas from complexity science and social network analysis to help organizations better understand how to create organizational conditions that are likely to lead to productive emergence. Cycles of emergence can occur at a variety of scales in an organization, from the emergence of new work patterns in a small work group to restructuring of the entire organization. Within each cycle, the role of the leader is to create the conditions for productive emergence to occur and then to take the productive results from this process (not all results will be productive) and ensure that these are integrated into the organization (Schreiber & Carley, 2008).

Plowman et al., (2007) identify three key mechanisms that leaders can and should use to encourage and support emergence: 1) disrupting existing patterns, 2) encouraging novelty, and 3) acting as sensemakers. They based these mechanisms on a review of the literature on traditional and complexity views of leadership along with a rich case study of transformation of an urban church. They found that disruption of existing patterns is necessary for new ideas to emerge. Leaders can amplify or reinforce existing disruption from the external environment (e.g., changing market conditions) (Goldstein et al., 2010), or intentionally disrupt existing patterns by, for example developing heterogeneous working groups (Uhl Bien and Marion, 2009). The tension created by disruption of existing patterns creates the conditions for new ideas to emerge. Yet, emergence of new ideas does not result just from disruption. Members of the organization need to feel some degree of interdependence and be working towards a simple and understandable goal, conditions which can and should be fostered by leaders (Uhl-Bien &
Finally, leaders need to act as sensemakers. This can occur through the recognition and amplification of good ideas developed in one pocket of the organization to the broader organization (Goldstein et al., 2010) and by using consistent language to connect good ideas to core organizational goals. These aspects of complexity leadership are summarized in Table 5.

Table 5. Summary of Leader Actions from a Complexity Leadership Perspective. (Adapted from Plowman et al., 2007).

<table>
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<tr>
<th>Leadership Mechanism</th>
<th>Comparison between complex leadership and traditional leadership.</th>
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<tbody>
<tr>
<td>Disrupt existing patterns</td>
<td>Complex leaders enable emergent futures by disrupting existing patterns through the use of conflict and uncertainty; whereas traditional leaders create knowable futures by minimizing conflict and eliminating uncertainty.</td>
</tr>
<tr>
<td>Encourage novelty</td>
<td>Complex leaders enable emergent self-organization by encouraging innovation through the articulation of simple goals and the promotion of autonomous interdependence; whereas traditional leaders operate as controllers by leading through command and control.</td>
</tr>
<tr>
<td>Act as sensemakers</td>
<td>Complex leaders enable emergent self-organization by interpreting emerging events and amplifying good ideas; whereas traditional leaders operate as controllers by directing order.</td>
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Complexity leadership ideas are promising because they have been shown to be productive in understanding leadership in business settings (e.g., Goldstein et al., 2010; Uhl-Bien & Marion, 2009; Uhl-Bien et al., 2007). We recommend that future research efforts explore this promise.

**Complexity leadership example.** We are not aware of the application of complexity leadership theory in higher education settings. Thus, we draw this example from the nonprofit sector. Plowman et al. (2007) conducted a case study of the transformation of “Mission Church”. Within a short period of time, this downtown Church in an urban center reversed a
fifty-year decline to become a vibrant community focused on advocacy and support for the city’s poor. The authors interpreted the case study through the three complexity leadership mechanisms described in Table 5. The Church leadership disrupted existing patterns by highlighting conflict and uncertainty about the future (e.g., internal conflicts between members of the organization) and also encouraging new voices to enter the conversation. They promoted novelty by applying heuristics (e.g., “What would Jesus do?”) and fostering interactions among community members. Finally, the Church leadership facilitated sensemaking by labeling behaviors and helping the Church develop a common language to describe its emerging focus on homeless ministry. The authors conclude by summarizing their complexity leadership perspective in which the role of leaders is to “help organizations take the moment and make the best of it, without knowing what is going to happen next” (p. 355).

**Developing Shared Vision (Category IV) Summary**

This category of change strategies emphasizes the importance of innovations coming from the front lines of the organization and the importance of these innovations being developed by groups of individuals with diverse perspectives. The learning organization perspective emphasizes the importance of middle managers in the knowledge creation process by mediating the interactions among knowledge producers on the front lines and incorporating this knowledge into organizational operations. The complexity leadership perspective emphasizes disruption and the role of organizational leaders (at all levels) to recognize and incorporate new ideas and practices into organizational operations. These concepts of emergence and organizational learning are important new focus areas for research on change in higher education.
Discussion

For several decades, researchers have attempted to make sense of the complex interplay and scales of STEM higher education change specifically and the relationships between organizational and individual change more generally. The cutting edge of this work maps out the variety of perspectives on change with respect to each other. We based this paper on one of these frameworks (Henderson et al., 2011; Henderson et al., 2010). Now that we have established that different approaches to change exist and articulated some of the relationships between these approaches, an important next step for change researchers would be to understand under what circumstances which approaches work best, and what are particularly powerful combinations of different approaches. It is sensible to assume that employing multiple perspectives on change will lead to better results, but the fact remains that there is little theoretical or empirical evidence to support or refine this assertion.

STEM higher education change agents are ready for a fresh perspective on change, even though there are many aspects of diffusion and implementation (Category I, Disseminating Curriculum & Pedagogy) yet to be explored. In STEM higher education change, many of us believe too much effort has gone into creating plug-and-play curriculum modules that are not flexible enough for independent-minded instructors to comfortably use. Similarly, accreditation (quality assurance, Category III) has a bad reputation as a change strategy since reforms adopted in 2000 have stagnated. (In fact, it is more common to hear ABET accreditation cited as a barrier than a strategy.) The literature helps us understand that quality assurance in higher education should not be considered as a cutting-edge change strategy; rather, the approach is suited to bringing a large number of programs up to a minimum standard. Faculty learning communities and their variations (Category II, Developing Reflective Teachers) are seeing increasing use, for
example in projects funded by NSF’s Widening Implementation and Demonstration of Evidence-based Reforms (WIDER) program (National Science Foundation, n.d.) . Considering new strategies will require a compromise between familiar and new approaches to change. The greatest opportunity for novelty is Category IV: Developing Shared Vision. There are precious few published examples of how STEM educators have employed strategies such as learning organizations and complexity leadership for the purposes of instructional change. Yet there is a lot of enthusiasm for exploring this category and creatively combining strategies from multiple categories. This requires letting go of some control, just as many teaching innovations expect of instructors. Change agents must take on a less familiar role of a facilitator who adjusts to new information and uncertain situations.

A more appropriate approach than focusing exclusively on Category IV would be to develop systems-level thinking about how various change initiatives focus on different aspects of STEM higher education and therefore complement each other (Groff, 2013). Over time and across initiatives, it is wise to employ a range of different perspectives. Focusing too narrowly on one perspective increases the chances of overlooking influential factors and processes. Collectively, our change efforts and investigations should be considering all four quadrants of Figure 1 to encompass a variety of approaches and frames for addressing “the problem” of improving undergraduate STEM education. This is similar to the complementary insights gained by considering the results of both quantitative and qualitative studies – for example, of the complex phenomena underlying student retention—single studies use a particular approach, but the whole picture is understood much better in the context of a variety of approaches. An important key to these advances is connecting studies that follow a different change strategy or
theory by contextualizing them in the bigger picture of alternative foci and approaches (i.e., the four categories presented here).

Considering a diversity of change strategies across the STEM educational system would require a diverse set of goals focusing at different levels. In STEM education, prescriptive outcomes have traditionally focused on very specific content or learning outcomes and have diffused through disciplinary or sub-disciplinary networks (e.g., mechanics, thermal sciences). This stands in stark contrast to organization-focused change strategies across a department or college of engineering. We are not necessarily saying that the categories presented here are incompatible, but they have traditionally been undertaken by different groups working toward the same broad agenda of STEM higher education instructional change. A systems thinking perspective could help coordinate these efforts better, for example, so that important connections could be made to leverage multiple strategies. This is a fundamentally different recommendation than suggesting everyone should be working in Category IV on complexity leadership approaches.

Finally, this paper has focused on efforts to change instructors, but it is interesting to consider the implications of various strategies on students. The goal of these instructional changes is to produce students who are more innovative, flexible, teamwork-oriented and able to navigate complexity and ambiguity. Engineering instructors and engineering educational environments should be modeling these skills and values for students, and in some cases actively engaging students in change initiatives. Getting out of the familiar Disseminating Courses and Curricula category (I) opens up creativity (emergent categories, II and IV) and collaboration (environments and structures categories, III and IV).
Conclusion

There is strong evidence that most people consider a single perspective or a limited set of perspectives when they consider change (e.g., Henderson et al., 2011). This is at least in part because underlying assumptions about change often remain implicit. In this review, we have tried to make them explicit.

Choice of change strategy for any specific situation should be based on many factors, such as the type and specificity of change desired, the resources available, and the power and position of the change agent. We can’t emphasize enough the importance of identifying a theory and using it to communicate your assumptions, emphases, and interpretations. Being explicit about the theoretical perspective guiding the change initiative and study or evaluation of the initiative will help to advance our collective thinking and make sense of the myriad approaches and perspectives on change.

There is particular interest in complexity theories and systems-level perspectives, which attempt to integrate a diverse set of influences. Although significantly absent from current practice within STEM education, documents such as the call for papers for this special issue are increasingly emphasizing complexity and systems approaches to change. This certainly has the potential to be the most transformational of the strategies. Transformation is currently in vogue, likely due to dissatisfaction with the rate of undergraduate STEM instructional change. However, not every change effort should aspire to be transformational. Small-scale changes and incremental improvements are important steps toward long-term goals of changing undergraduate STEM education for the better. It is through coordinated work at multiple levels that true transformational change is likely to occur. It may be that the most important step we can take toward transforming undergraduate STEM lies in informing and evaluating our change
efforts by linking them to theory, and in understanding the limitations of any one particular strategy. In order for change efforts to be truly scholarly, change agents should articulate their change strategy and collect and report evidence to evaluate the effectiveness of the strategy. In reports and articles, strategies should be situated in the broader context of possible strategies that could have been selected. This will ensure that STEM education efforts continue to build upon each other and have the desired—and ultimately transformational—impact.

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