Surveying the Landscape of Professional Development Research: Suggestions for New Perspectives in Design and Research

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ABSTRACT

Science, technology, engineering, and mathematics (STEM) higher education is in need of improved teaching methods to increase learning for all students. Faculty professional development programs are a widespread strategy for fostering this improvement. Studies of faculty development programs have focused on program design and the impact of surrounding context, including both social supports for learning and institutional context. I reviewed these approaches, as well as work that focused on the faculty experience, and suggest that a larger perspective that encompasses learning over time and the interactions between disciplinary and institutional learning opportunities is important. This leads to both new design considerations and new research questions that focus on increasing faculty skill in learning about teaching and applying the results, as well as improving the impact of professional development beyond the immediate participants. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/17-281.1]

Key words: professional development, faculty learning, research agenda, professional development design

INTRODUCTION

A hallmark of higher education is continual engagement of faculty in learning within their academic specialty. This is supported by the conduct of research, participation in a professional community through publications and meetings, skill-building short courses, and ongoing scholarly reading. We all know how important it is to "stay current" in our discipline.

We are less schooled in "staying current" in our teaching—perhaps because undergraduate geoscience teaching evolved relatively slowly in the past century. However, today teaching is evolving very rapidly as computation and communication strategies change, allowing new approaches to teaching with data, new ways of supporting students' skill development, new ways of interacting with students, and more. Further, cognitive science and educational research, including geoscience education research, are active fields where new insights that can inform our teaching are continually generated. Ongoing opportunities to learn from our colleagues about teaching are no less important today than ongoing interactions with research or disciplinary colleagues about progress in the discipline.

Improving science, technology, engineering, and mathematics (STEM) teaching at the undergraduate level has been a national priority for the last 20 years (NSF, 1996; PCAST, 2012). We need stronger undergraduate STEM learning to support the STEM workforce, a growing sector in our economy (Carnevale et al., 2011), and to create a citizenry that can capitalize on science to live sustainably, justly, and well (NAS, 2016). In particular, there is concern that engaged pedagogies known to improve learning, especially for groups underrepresented in the sciences, are not widely implemented (NRC, 2012; Freeman et al., 2014).

However, the culture and structures that support learning about teaching are less well developed than those that support learning within the science disciplines. As a result, the National Science Foundation and others have made substantial investments in programs that support faculty learning about STEM pedagogy, primarily within a discipline (NRC, 2012). Institutions of higher education are also investing in this area, for example, by creating STEM education centers as a mechanism to support improvements in teaching (NSEC, 2017). Many approaches have been tried to support faculty, and there is now a substantial research field studying their impact to discern those things that best help to improve teaching.

While professional development that focuses on faculty learning in support of changes in instruction is widely viewed as a promising approach (PCAST, 2012), there are other strategies that can be used to improve teaching as well. Borrego and Henderson (2014) reviewed eight distinct strategies for improving instruction, only four of which focused on the faculty member and fell within the realm of professional development. Other strategies include policies strengthening accountability of the institution for quality instruction, focusing on strong leadership for change, and approaches that focus on the culture and conditions supporting change within an institution. As described herein, the context in which faculty are working impacts their ability and motivation to change their instructional methods.

In this commentary, I will paint with broad strokes the research on faculty professional development, which has focused largely on the design of the professional development activity and its results, including a strong focus on the context in which the activity takes place. I will draw in research on other forms of professional learning to illuminate these results. Turning to work that focuses on the faculty member, I will suggest that we may be missing an important perspective—the learner as an active agent who learns over time and is responsible for making changes.

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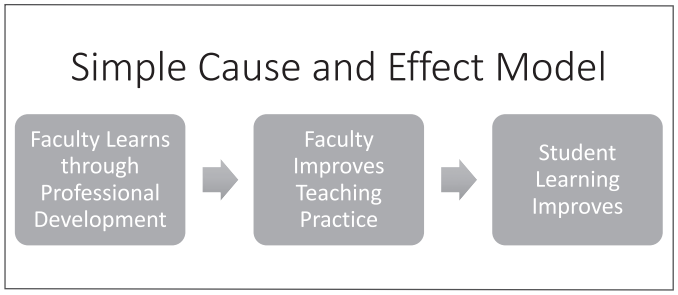

FIGURE 1: Simple cause-and-effect model for professional development shows pathway from faculty development to student learning. Drawn from work of Desimone et al. (2009).

A SIMPLE CAUSE-AND-EFFECT MODEL FOR PROFESSIONAL DEVELOPMENT

A straightforward way to think about professional development activities uses a simple cause-and-effect model (Fig. 1). Faculty learn about teaching, and this causes them to change their teaching, which in turn causes students to learn more (Desimone et al., 2009). This model is implied when one claims that an effective way to improve student learning is to provide faculty development—an argument that is commonly used in both K–12 settings (PCAST, 2010) and higher education (PCAST, 2012).

There are two important steps in the model that involve faculty: They learn from the professional development, and they change their teaching. When a professional development program is evaluated by looking to see if individual participants changed their teaching, this logic model is underpinning the evaluation design. This is not an uncommon strategy, and it is often implemented with a self-report survey (e.g., Pfund et al., 2009; Ho et al., 2001). For example, On the Cutting Edge and Earth Educators' Rendezvous exit evaluations ask faculty what they learned at the workshop and how they plan to use it in their teaching (McLaughlin et al., 2005); these questions make sense in light of this logic model.

Survey results rely on the accuracy with which faculty self-report their learning and behavior. This accuracy has been called into question (Ebert-May et al., 2011; AAAS, 2013). As a result, several studies have used classroom observations to better understand impact, either analyzing video (e.g., Ebert-May et al., 2011, 2015; Lund et al., 2015; for a contrasting viewpoint, see Smith et al., 2014) or making visits to classrooms (e.g., Budd et al., 2013; Smith et al., 2014; Teasdale et al., 2017). The On the Cutting Edge Classroom Observation Project has been making such observations in the geosciences for several projects (On the Cutting Edge, 2017).

Relatively few studies have followed a specific faculty development project all of the way to impact on student learning. This was undertaken successfully at Washington State University in studies of the Critical Thinking Project (Condon et al., 2016). Scoring of assignments and associated student work showed improvement on both short and long time scales after participation in faculty professional development. A similar study at Carleton College showed how difficult this can be. Careful alignment between the professional development programming and the measures of assignment improvement and student learning appears to be very important (Condon et al., 2016).

A strength of the simple cause-and-effect model is that it allows one to compare across successful professional development activities to identify common elements. These are then hypothesized to be the critical elements of a successful intervention (e.g., Garet et al., 2001). One can also use a meta-analysis approach across smaller studies to extract critical elements of a successful intervention (e.g., Henderson et al., 2011).

Drawing upon these types of studies, a National Academies consensus study (NRC, 2012) concluded that successful professional development aimed at translating research into practice included three key elements:

- sustained, focused efforts, lasting 4 weeks, one semester, or longer,
- feedback on instructional practice, and
- a deliberate focus on changing faculty conceptions about teaching and learning.

The consensus study noted, however, that there were some programs that appeared to be successful while not meeting the first of these criteria. The On the Cutting Edge program in the geosciences is one of these programs.

Review articles considering a wider range of data also demonstrate the challenges of this approach. Professional development experiences are widely different in their design and make use of a number of fundamentally different underpinning philosophies as to how to best support quality instruction (Henderson et al., 2011; Amundsen and Wilson, 2012). The types of characteristics identified as important vary widely in form, reflecting the perspective of the review. For example:

- Emphasizing the use of cooperative teams (D'Avanzo, 2014): This characteristic describes the pedagogic design.
- Making robust use of mentoring and reflection (Ebert-May et al., 2015): This characteristic describes the interactions between the leaders and the participants within and beyond a specific workshop or activity.
- Being driven by a well-defined image of effective classroom learning and teaching and supporting teachers to serve in leadership roles (Loucks-Horsley et al., 2003): This characteristic describes the viewpoint of the designer.

Looking across these studies, there are two principles that appear to hold: (1) The design should be driven by the desired outcomes and guided by a theory of change (Loucks-Horsley et al., 2003) and (2) it should make use of teaching strategies grounded in research on learning, including adult learning (Wilson, 2013).

THE IMPORTANCE OF CONTEXT

Learning does not take place in a vacuum, nor for that matter do changes in one's teaching. Much of the variation in outcomes observed in the simple cause-and-effect model may be a result of this broader context. Two important contexts have been studied when trying to understand the success of professional development programs in higher

education: the community of learners that surrounds and supports an individual as they learn and change, and the institutional context that supports or impedes changes in practice.

As educators, we understand the importance of interactions among students in supporting learning. It stands to reason that the interactions among faculty and the ways in which these support learning and changes in instruction are no less important. Numerous approaches have been used to capitalize on peer interactions in faculty professional development programs, extending from providing a supportive community of peers that surrounds learning and implementation of a very specific pedagogy or practice, to establishing faculty groups for the purpose of fostering interaction that will lead to emergent learning. The former efforts are often described as communities of practice (Wenger et al., 2002). Faculty learning communities are a good example of the latter (Cox, 2004). Groups spanning this spectrum have been used to support faculty learning on a single campus, as well as across campuses using both face-to-face and virtual activities. For example, the Center for the Integration of Research, Teaching and Learning (CIRTL) program has a well-developed set of virtual activities that support graduate students in staying engaged with their colleagues as they learn to teach (https://www.cirtl.net/), and the Quantitative Undergraduate Biology Education and Synthesis (QUBES) network has an ongoing mentoring program for biology faculty to support implementation of quantitative teaching materials (https://qubeshub.org/).

Kezar and Gehrke have studied national-scale communities of faculty, which they call communities of transformation, recognizing that they are not strictly a community of practice or a network (Kezar and Gehrke, 2015; Gehrke and Kezar, 2016). Surveying faculty participants in four communities of transformation, they established that participants feel that they are learning and improving practice as a result of participation and that their participation in the community is reenergizing. These results are very similar to those reported in qualitative studies of the On the Cutting Edge program, where participants reported learning and changing their practice as well as finding the workshop program motivational (McLaughlin et al., 2010; Rockman et al., 2013; Manduca et al., 2017).

While communities of practice, faculty learning communities, and communities of transformation are all acting on time scales of a year or longer, peer interactions are also important within a specific workshop or event. D'Avanzo (2014), in her review of professional development in biology, recognized two different ways in which the faculty at the workshop are critical. She recommended the following features:

- Give faculty a central role in critical aspects of the professional development program.
- Emphasize cooperative teams of faculty members who work together effectively to transform teaching.

The first recommendation is focused on peer instruction at workshops. The second is focused on cooperative learning. While the value of cooperative learning is well established in literature on learning (e.g., Johnson and Johnson, 1999), the importance of peer instruction is illuminated more fully in the literature from human resource development (HRD) focused on training and transfer to the workplace.

Figuring out how to change professional behavior is of high interest well beyond the halls of academia. HRD focuses on the use of training to improve practice in all kinds of businesses, from medicine to manufacturing. This work has developed a comprehensive model of the relationships among the learner, the learning, the work, and the work environment (Baldwin and Ford, 1988; Holton, 2005; Gitonga, 2007; Cheng and Hampson, 2008; Russ-Eft and Preskill, 2009). These models, like the simple cause-and-effect model, distinguish between learning at the workshop and transfer to the work environment. Holton, in particular, provided a framework for understanding this transfer. Of the 16 constructs in this framework, my colleagues and I identified three that appear related to peer instruction (Manduca et al., 2017). They suggest that peer instruction is powerful because faculty members view their colleagues as a trusted source of information and guidance. This trust is grounded in the belief that their peers understand their teaching situation and thus are likely to give them strong, practical advice based on experience. Further, the success of their peers strengthens their belief that they too can implement the change. A fourth construct in the Holton framework is related to peer interaction, where faculty members are encouraged and supported by interactions with like-minded peers—a finding supported by the work by Kezar and Gehrke (2015). Working with peers is a powerful context.

The importance of the institutional environment in promoting or impeding change in teaching practice has been the subject of much discussion. From teaching spaces and teaching loads to institutional reward systems, factors beyond the control of individual faculty clearly play an important role in the amount of change even the most committed individual can make. The importance of the work environment is also recognized in the HRD frameworks for transfer. Both theoretical and case study approaches are being used to understand the necessary institutional context to promote improvements in teaching (Austin, 2011; Henderson et al., 2015; AAU, 2016; Condon et al., 2016). These studies explore the structural and cultural aspects of the institution and the ways in which they promote or impede quality instruction. For example, Condon et al. (2016) explored the importance of faculty and administration holding a shared value for learning about teaching, while AAU case studies described the importance of department- or college-wide initiatives, as well as resources, rewards, and incentives. Austin (2011) described the institution as a system operating in a larger societal context and identified the reward system, workloads, and institutional leadership, in addition to professional development, as powerful levers for change. A thorough review of the evolution and history of professional development was provided by Beach et al. (2016).

A FOCUS ON THE LEARNER

So far, I have looked primarily at the learning opportunity and the surrounding supportive (or hindering) context. The faculty member him/herself is also central to the process of change. In HRD models, the learner's motivation first to learn and then to make use of their learning is a

critical element. Research focused directly on the faculty member can take the form of interviews investigating the faculty member's experience learning about, experimenting with, and then adopting or discarding a teaching method (e.g., Dancy et al., 2016). Alternatively, it can investigate the faculty experience in any step along the way, for example, studying the motivation of faculty to participate in professional development (e.g., Lowenthal et al., 2013), or the changes in their beliefs resulting from a professional development experience (e.g., Brownell and Tanner, 2012; Pelch and McConnell, 2016).

I was part of a large study at Carleton that used an ethnographic approach involving direct observation, interviews, and artifact analysis to understand faculty learning and its relationship to teaching over time at Carleton College and Washington State University (Condon et al., 2016). One of the primary findings was that the relationship between learning and changes in teaching is not as direct as is suggested by the simple cause-and-effect model, even when one takes into account the effects of context. Rather, faculty learning about teaching was observed as an ongoing process, very similar to the way one learns within one's academic discipline (Neumann, 2009). Ideas are explored through venues as wide ranging as reading articles, attending workshops, engaging in projects, reflecting on experience, and talking to colleagues. Learning is integrated over time into a useable body of knowledge. Changes in teaching can draw on recent lessons or ones from many years prior. In most cases, changes in teaching are incremental. The skill of the faculty member as a student of teaching is critical, just as their ability to learn within their discipline is crucial to their research success. The strength of an individual faculty member's progress in teaching and their progress in research both depend on their motivation and ability to gather knowledge and ideas from different sources and to apply them effectively to their practice.

These findings put the faculty member, not the professional development activities, at the center of the picture (Fig. 2). This view is aligned with that of researchers studying faculty work and careers who focus centrally on the faculty member and their development over time (e.g., O'Meara et al., 2008). The role of professional development in this context becomes one of supporting ongoing learning and professional growth around teaching. The learning landscape for the faculty member includes a suite of opportunities at the institution, in their discipline, and elsewhere in their lives that feed their learning and the subsequent evolution of their practice.

This perspective requires a mind shift when thinking about faculty development. If our goal is to develop faculty members who are most able to engage in higher-order thinking about their teaching over time and act on their knowledge, it becomes important to strengthen their skills with learning and application of new knowledge. That is, we must work to develop the metacognition that supports their teaching practice. The Scholarship of Teaching and Learning movement, which focuses on supporting individual and communal study of and reflection on classroom experience, is one approach to this work (Hutchings and Shulman, 1999). In addition, supporting volition, the will to act, is essential.

For the design of professional development programs, this perspective means that the ways in which any professional development program connects to other programs are important, both within the discipline and within the institution. The connection of ideas between learning opportunities is critical to ongoing growth and transfer of learning to teaching. The linking together of learning opportunities is the mechanism by which an individual faculty member creates a pathway for continual learning and improvement. Thus, important questions in the design of an individual professional development program become: How does the program work to facilitate transfer of prior knowledge to this new learning situation? How does it foster integration of new knowledge with previous learning? How does it link to support structures for implementation at the home institution or within the discipline? Thinking about the set of professional development activities within an institution or discipline, one could ask, how in this set are metacognition and volition addressed? This is a design process similar to looking at the curriculum of a degree program and asking how are quantitative and writing skills supported and addressed across the curriculum (e.g., Mogk, 2013).

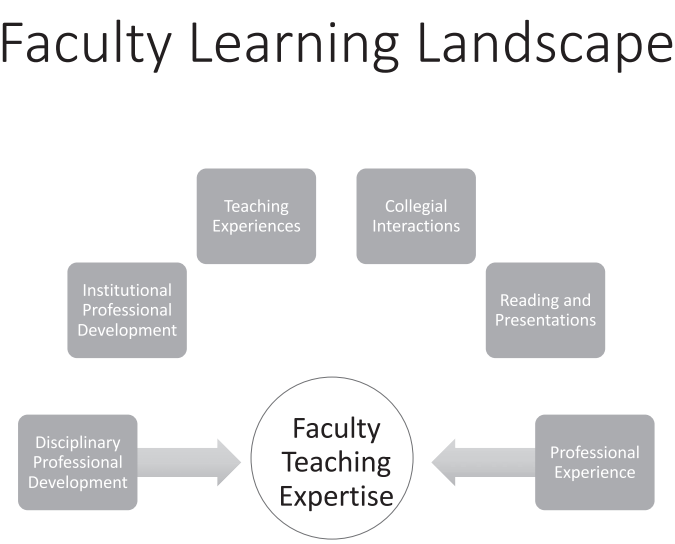

FIGURE 2: Faculty-centered model for professional growth shows expertise building from multiple learning opportunities over time.

This perspective also suggests a new set of research questions for understanding faculty learning and the role of professional development: How do faculty members become expert learners in the realm of teaching? How do faculty members select from the palate of opportunities that are available to them? How do they integrate and use knowledge? What supports their ability to create impactful changes in their teaching?

A recent analysis of the Geoscience Faculty Survey data showed that there is a population of geoscience faculty who are actively engaged in learning about teaching, capitalizing on multiple learning opportunities (Manduca et al., 2017). Members of this group of faculty are more likely than others to use many types of effective teaching practices. We suggested that this group may be exhibiting the ongoing learning and application to teaching observed in the Condon et al. (2016) study. Studies of this group could provide an interesting perspective on learning within the discipline.

A SYSTEMS PERSPECTIVE

The Condon et al. (2016) study had a second interesting finding. They showed that knowledge about teaching spreads across the campus through a myriad of channels, raising the level of expertise on the campus as a whole. This flow of information is related to the concept of systems fitness or health from studies that use a systems perspective to design and evaluate change strategies (Kania et al., 2014; Preskill et al., 2014; Kastens and Manduca, 2017). In a healthy system, information flows and system structure combine to allow productive change to emerge. In the examples described by Condon et al. (2016), the system would be a university department or a liberal arts college. Healthy systems, in this case, have a strong culture of teaching and learning that brings information about teaching into the system, supports spread of this information across the system, and empowers faculty to respond with changes in their teaching. The individual actors in this system are motivated to learn about teaching, integrate new learning into a rich understanding of teaching and learning, and draw upon this knowledge to modify their teaching in appropriate ways.

While Condon et al. (2016) were looking at flow of information within a campus, there are also flows of information into a campus. Gehrke and Kezar (2016) reported that in some cases, participants take learning from a community of transformation back into their own institution, supporting change on campus. A similar effect was seen in the evaluation of the On the Cutting Edge program in the geosciences (McLaughlin et al., 2010). The impact on an individual campus is increased if multiple individuals from a campus are involved (Gehrke and Kezar, 2016). Faculty live at the intersection of two worlds: their discipline and their institution. Both provide opportunities to learn about teaching and supports for change. We need to understand how these opportunities intersect and become reinforcing.

The goal of promoting a healthy system that spreads information and supports change also suggests some new design considerations and some new research questions for professional development programs. For designers, it is important to ask: How does my design support or accelerate the spread of information beyond the original participants? This was a key design principle for the On the Cutting Edge program from its inception. The resulting Web site (https://serc.carleton.edu/NAGTWorkshops/) may explain why the effect of its workshops has been stronger than predicted by current theories that emphasize the importance of long-term interactions (NRC, 2012). This, of course, is a research question, and it suggests a broader area of study: What is the impact of professional development programs beyond the direct participants? How does that impact occur? What features support that impact?

LOOKING FORWARD

Following on the work of Condon et al. (2016), I have suggested that by taking a faculty-centered view, professional development activities appear as events in a much longer arc of individual faculty learning, and that the impact of these activities radiates across communities and over time. By shifting to this frame, we add interaction effects between professional development opportunities to the already complicated work of comparing different types and designs of professional development activities. It becomes critical to understand the intersections between professional development opportunities in the discipline and those in the institution. Understanding the social context that promotes change and the institutional barriers that impede it across the larger context is critical.

However, as geoscientists will appreciate, understanding that an event is part of a bigger picture does not negate a focus on the event. We study individual faults and compare the results to make sense of fault mechanics. So too should we continue to study individual professional development programs and compare results to make sense of professional learning. Likewise, complicated contextual variables do not make understanding impossible. Modeling, case comparisons, and the use of taxonomy are tried and true methodologies that geoscientists bring to such problems (Ault, 1998; Manduca and Kastens, 2012). If we wish to understand effective programming that leads to ongoing and substantial improvement in teaching, we must combine studies of professional development events with studies that follow the history of individuals, and studies of the larger system interactions that support change and growth. This work is well underway in a variety of places. Just as success in understanding the Earth system required bringing together communities studying oceans, atmosphere, and solid Earth, we must continue to engage more fully with communities studying HRD, institutional change, faculty learning, and professional development in STEM disciplines. Good thing geoscientists like to collaborate.

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REFERENCES

American Association for the Advancement of Science (AAAS). 2013. Describing & measuring undergraduate STEM teaching practices. Washington, DC: AAAS.

American Association of Universities (AAU). 2016. Improving undergraduate STEM education at research universities: A collection of case studies. Phoenix, AZ: Research Corporation for Science Advancement.

Amundsen, C., and Wilson, M. 2012. Are we asking the right questions?: A conceptual review of educational development literature in higher education. *Review of Educational Research*, 82:90–126.

Ault, C.R., Jr., 1998. Criteria of excellence for geological inquiry: The necessity of ambiguity. *Journal of Research in Science Teaching*, 25:189–212.

Austin, A., 2011. Promoting evidence-based change in undergraduate science education. Paper Commissioned by the National Research Council Board on Science Education. Available at http://sites.nationalacademies.org/DBASSE/BOSE/DBASSE_080124 (accessed 3 June 2017).

Baldwin, T.T., and Ford, J.K. 1988. Transfer of training: A review and directions for future research. *Personnel Psychology*, 41:62–105.

Beach, A.L., Sorcinelli, M.D., Austin, A.E., and Rivard, J.K. 2016, Faculty development in the age of evidence: Current practices, future imperatives. Sterling, VA: Stylus.

Borrego, M., and Henderson, C. 2014. Increasing the use of evidence-based teaching in STEM higher education: A comparison of eight change strategies. *Journal of Engineering Education*, 103:220–252.

Brownell, S.E., and Tanner, K.D. 2012. Barriers to faculty pedagogical change: Lack of training, time, incentives, and . . .tensions with professional identity?. *CBE-Life Sciences Education*, 11:339–346.

Budd, D.A., Kraft, K., McConnell, D.A., and Vislova, T. 2013. Characterizing teaching in introductory geology courses: Measuring classroom practices. *Journal of Geoscience Education*, 61:461–475.

Carnevale, A.P., Smith, N., and Melton, M. 2011. STEM: Science Technology Engineering Mathematics Georgetown University Center for Education and the Workforce. Available at https://cew.georgetown.edu/cew-reports/stem/ (accessed 12 September 2017).

Cheng, E.W.L., and Hampson, I. 2008. Transfer of training: A review and new insights. *International Journal of Management Reviews*, 10:327–341.

Condon, W., Iverson, E.R., Manduca, C.A., Rutz, C., and Willett, G. 2016. Faculty development and student learning: Assessing the connections. Bloomington, IN: Indiana University Press.

Cox, M.D., 2004. Introduction to faculty learning communities. *New Directions for Teaching and Learning*, 2004:5–23.

Dancy, M., Henderson, C., and Turpen, C. 2016. How faculty learn about and implement research-based instructional strategies: The case of peer instruction. *Physical Review Physics Education Research*, 12:010110.

D'Avanzo, C. 2014. Post–vision and change: Do we know how to change? *CBE-Life Sciences Education*, 12:373–382.

Desimone, L., Smith, T.M., and Friswold, D.E. 2009. Survey measures of classroom instruction: Comparing student and teacher reports. *Educational Policy*, 24:267–329.

Ebert-May, D., Derting, T.L., Henkel, T.P., Maher, J.M., Momsen, J.L., Arnold, B., and Passmore, H.A., 2015. Breaking the cycle: Future faculty begin teaching with learner-centered strategies after professional development. *CBE-Life Science Education*, 14:1–12.

Ebert-May, D., Derting, T.L., Hodder, J., Momsen, J.L., Long, T.M., and Jardeleza, S.E. 2011. What we say is not what we do: Effective evaluation of faculty professional development programs. *BioScience*, 61:550–558.

Freeman, S., Eddy, S.L., McDonough, M., Smith, M.K., Okoroafor, N., Jordt, H., and Wenderoth, M.P. 2014. Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences of the United States of America*, 111:8410–8415.

Garet, M.S., Porter, A.C., Desimone, L., Birman, B.F., and Yoon, K.S. 2001. What makes professional development effective? Results from a national sample of teachers. *American Educational Research Journal*, 38:915–945.

Gehrke, S., and Kezar, A., 2016. STEM reform outcomes through communities of transformation. *Change*, 48:30–38.

Gitonga, J., 2007. Transfer of learning in continuing medical education (CME): A conceptual model. *In* Proceedings of the International Research Conference in the Americas of the Academy of Human Resource Development. Indianapolis, IN. Available at http://files.eric.ed.gov/fulltext/ED504737.pdf (accessed 10 August 2017).

Henderson, C., Beach, A., and Finkelstein, N. 2011. Facilitating change in undergraduate STEM instructional practices: An analytic review of the literature. *Journal of Research in Science Teaching*, 48:952–984.

Henderson, C., Mestre, J.P., and Slakey, L.L. 2015. Cognitive science research can improve undergraduate STEM instruction: What are the barriers? *Policy Insights from the Behavioral and Brain Sciences*, 2(1):51–60. Available at http://journals.sagepub.com/doi/abs/10.1177/2372732215601115 (accessed 3 June 2017).

Ho, A., Watkins, D., and Kelly, M. 2001. The conceptual change approach to improving teaching and learning: An evaluation of a Hong Kong staff development programme. *Higher Education*, 42:143–169.

Holton, E.F. 2005. Holton's evaluation model: New evidence and construct elaborations. *Advances in Developing Human Resources*, 7:37–54.

Hutchings, P., and Shulman, L.S. 1999. The scholarship of teaching: New elaborations. New developments. *Change*, 31:11–15.

Johnson, D.W., and Johnson, R. 1999. Learning together and alone: Cooperative, competitive, and individualistic learning, 5th ed. Boston, MA: Allyn and Bacon.

Kania, J., Kramer, M., and Russell, P. 2014. Strategic philanthropy for a complex world. *Stanford Social Innovations Review*, 12(3).

Kastens, K.A., and Manduca, C.A. 2017. Using systems thinking in the design, implementation and evaluation of complex educational innovations, with examples from the InTeGrate project. *Journal of Geoscience Education*, 65(3):219–230.

Kezar, A., and Gehrke, S. 2015. Communities of transformation and their work scaling STEM reform. Los Angeles, CA: University of Southern California. Available at http://www.uscrossier.org/pullias/wp-content/uploads/2016/01/communities-of-trans.pdf (accessed on 3 June 2017).

Loucks-Horsley, S., Stiles, K.E., Mundry, S.E., and Love, N.B. 2003. Designing professional development for teachers of science and mathematics, 2nd ed. Thousand Oaks, CA: Corwin Press, Inc.

Lowenthal, P.R., Wray, M.L., Bates, B., Switzer, T., and Stevens, E. 2013. Examining faculty motivation to participate in faculty development. *International Journal of University Teaching and Faculty Development*, 3:149–164.

Lund, T.J., Pilarz, M., Velasco, J.B., Chakraverty, D., Rosploch, K., Undersander, M., and Stains, M. 2015. The best of both worlds: Building on the COPUS and RTOP observation protocols to easily and reliably measure various levels of reformed instructional practice. *CBE-Life Science Education*, 14:1–12.

Manduca, C., Iverson, E., Luxenberg, M., Macdonald, R.H., McConnell, D., Mogk, D., and Tewksbury, B. 2017. Improving undergraduate STEM education: The efficacy of discipline-based professional development. *Science Advances*, 3(2):e1600193.

Manduca, C.A., and Kastens, K.A. 2012. Geoscience and geoscientists: Uniquely equipped to study Earth. *In* Kastens, K.A., and Manduca, C.A., eds., Earth and mind II: A synthesis of research on thinking and learning in the geosciences. Boulder, CO: Geological Society of America, Special Paper 486, p. 1–12.

McLaughlin, J.A., Iverson, E., Kirkendall, R., Manduca, C., and Bruckner, M. 2010. On the Cutting Edge 2010 evaluation report. Northfield, MN: Science Education Resource Center. Available at https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/2009_cutting_edge_evaluation_1265409435.pdf. (accessed 4 June 2017).

McLaughlin, J.A., Iverson, E., and Manduca, C. 2005. On the Cutting Edge 2005 evaluation report. Northfield, MN: Science Education Resource Center. Available at https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/full_summary.v6.doc (accessed 7 August 2017).

Mogk, D.W. 2013. Curriculum by design. Earth and Mind: The Blog. Available at https://serc.carleton.edu/earthandmind/posts/curriculum_desi.html (accessed 4 June 2017).

National Academies of Sciences, Engineering, and Medicine (NAS).

2016. Science literacy: Concepts, contexts, and consequences. Washington, DC: The National Academies Press.

National Research Council (NRC). 2012. Discipline-based education research: Understanding and improving learning in undergraduate science and engineering. Washington, DC: The National Academies Press.

National Science Foundation (NSF). 1996. Shaping the future: New expectations for undergraduate education in science, mathematics, engineering, and technology. Washington, DC: National Science Foundation.

Network of STEM Education Centers (NSEC). 2017. Campus centers in STEM education. Northfield, MN: Carleton College. https://serc.carleton.edu/StemEdCenters/campus_centers.html (accessed 3 June 2017).

Neumann, A. 2009. Professing to learn: Creating tenured lives and careers in the American research university. Baltimore, MD: The Johns Hopkins University Press.

O'Meara, K.T., LaPointe, A., and Neumann, A. 2008, Faculty careers and work lives: A professional growth perspective. San Francisco, CA: Jossey-Bass.

On the Cutting Edge. 2017. Classroom Observation Project: Understanding and improving our teaching using the Reformed Teaching Observation Protocol (RTOP): About this Project. Northfield, MN: Carleton College. Available at https://serc.carleton.edu/NAGTWorkshops/certop/about.html (accessed 7 August 2017).

Pelch, M.A., and McConnell, D.A. 2016. Challenging instructors to change: A mixed methods investigation on the effects of material development on the pedagogical beliefs of geoscience instructors. *International Journal of STEM Education*, 3:5. Available at https://stemeducationjournal.springeropen.com/articles/10.1186/s40594-016-0039-y (accessed 3 June 2017).

Pfund, C., Miller, S., Brenner, K., Bruns, P., Chang, A., Ebert-May, D., Fagen, A.P., Gentile, J., Gossens, S., Khan, I.M., Labov, J.B., Pribbenow, C.M., Susman, M., Tong, L., Wright, R., Yuan, R.T., Wood, W.B., and Handelsman, J. 2009. Summer institute to improve university science teaching. *Science*, 324:470–471.

President's Council of Advisors on Science and Technology (PCAST). 2010. Prepare and inspire: K–12 education in science, technology, engineering and math (STEM) for America's future. Washington, DC: Executive Office of the President.

President's Council of Advisors on Science and Technology (PCAST). 2012. Engage to excel: Producing one million additional college graduates with degrees in science, technology, engineering, and mathematics. Washington DC: Executive Office of the President.

Preskill, H., Gopal, S., Mack, K., and Cook, J. 2014. Evaluating complexity: Propositions for improving practice. FSG. Available at: http://www.fsg.org/publications/evaluating-complexity (accessed 31 October 2016).

Rockman et al–Research and Evaluation. 2013. On the Cutting Edge Project: Year 3 independent evaluation report. Northfield, MN: Science Education Resource Center. http://serc.carleton.edu/files/NAGTWorkshops/about/2013_external_evaluation_repor.pdf (accessed 3 June 2017).

Russ-Eft, D., and Preskill, H. 2009. Evaluation in organizations: A systemic approach to enhancing learning, performance, and change. New York: Basic Books.

Smith, M.K., Vinson, E.L., Smith, J.A., Lewin, J.D., and Stetzer, M.R. 2014. A campus-wide study of STEM courses: New perspectives on teaching practices and perceptions. *CBE-Life Science Education*, 13:624–635.

Teasdale, R., Viskupic, K., Bartley, J.K., McConnell, D., Manduca, C., Bruckner, M., Farthing, D., and Iverson, E. 2017. A multidimensional assessment of reformed teaching practice in geoscience classrooms. *Geosphere*, 13 13(2):608–627.

Wenger, E., McDermott, R., and Snyder, W. 2002. Cultivating communities of practice: A guide to managing knowledge. Boston, MA: Harvard Business School Press.

Wilson, S.M. 2013. Professional development for science teachers. *Science*, 19:310–313.