JOURNAL OF THE LEARNING SCIENCES, 25: 531–564, 2016

ISSN: 1050-8406 print / 1532-7809 online
DOI: 10.1080/10508406.2016.1207541

Routledge
Taylor & Francis Group

Organizing for Teacher Agency in Curricular Co-Design

Samuel Severance
School of Education and
Institute for Cognitive Science, Center for Innovation and Creativity
University of Colorado Boulder

William R. Penuel
School of Education
University of Colorado Boulder

Tamara Sumner
Institute of Cognitive Science, Center for Innovation and Creativity
University of Colorado Boulder

Heather Leary
McKay School of Education
Brigham Young University

Cultural-historical activity theory (CHAT) approaches to intervention aim for transformative agency, that is, collective actions that expand and bring about new possibilities for activity. In this article, we draw on CHAT as a resource for organizing design research that promotes teachers' agency in designing new science curriculum materials. We describe how CHAT informed our efforts to structure a collaborative design space in which teachers and other participants sought to develop new curriculum materials intended to help realize a new vision for science education. Specifically, we describe the tools and routines we deployed to support the design process, and we analyze the ways in which teachers took up elements of

Correspondence should be addressed to Samuel Severance, School of Education, University of Colorado Boulder, 249 UCB, Boulder, CO 80309. E-mail: severans@colorado.edu

Color versions of one or more figures in the article can be found online at http://www.tandfonline.com/hlns.

our design process as well as how they adapted, resisted, and suggested alternative tools and strategies to help develop new curriculum materials. In so doing, we illustrate ways in which CHAT can serve as a guide both for organizing collaborative design processes and for analyzing their efficacy.

Many education reforms offer visions for what teaching and learning within schools and districts should look like. Reform efforts, however, can fall short because they constrain teachers' opportunities to contribute their expertise toward achieving such visions (Snow, 2015). Teachers typically encounter these visions as new policies and guidance that circumscribe their autonomy in deciding what and how to teach (Allen & Penuel, 2015; Bryk, Gomez, Grunow, & LeMahieu, 2015). Historically and continuing today, two aspects of teachers' *agency* are limited within educational reform efforts, namely, their capacity to shape and define the course of the reform effort and their level of control or volition (Konopasky & Sheridan, 2016). This article describes a strategy for expanding these two aspects of teachers' agency.

Collaborative design, or *co-design*, in design-based research is one strategy for leveraging the expertise of teachers to design, implement, and test educational innovations and thereby expand teachers' agency within reform efforts. Co-design is a "a highly-facilitated, team-based process in which teachers, researchers, and developers work together in defined roles to design an educational innovation, realize the design in one or more prototypes, and evaluate each prototype's significance for addressing a concrete educational need" (Penuel, Roschelle, & Shechtman, 2007, p. 51). Co-design is inspired by the tradition of participatory design in Scandinavia, which has long promoted the agency of workers in the design of technologies and practices intended to transform the workplace (Ehn, 1992; Simonsen & Robertson, 2013). In Scandinavia, participatory design is an integral part of efforts to promote not just more usable technologies but also the ideals of workplace democracy, in which workers have a say in initiatives that affect their practice (Kensing & Greenbaum, 2013).

Co-design represents an emerging approach within the learning sciences for producing more usable innovations and for expanding teachers' agency in the process of improving teaching and learning. Learning scientists have explored co-design's potential for the design of curriculum materials (Peters & Slotta, 2009; Reiser et al., 2000), interactive technologies (Penuel et al., 2007; Spikol, Milrad, Maldonado, & Pea, 2009), teacher professional development (Voogt et al., 2015), and strategies for school and district reform (Cobb, Jackson, Smith, Sorum, & Henrick, 2013; Kwon, Wardrip, & Gomez, 2014). Most recently, co-design has become an integral part of community-based design research (Bang, Medin, Washinawatok, & Chapman, 2010) and social design experiments (Gutiérrez & Jurow, 2016/this issue; Taylor & Hall, 2013). In these projects, there are many examples of researchers acting as facilitators of co-design who successfully build a context for amplifying teachers' voices in conversation relative to those of administrators who might otherwise seek to constrain their autonomy (e.g., Penuel, Tatar, & Roschelle, 2004; Voogt et al., 2015).

In this article, we explore how cultural-historical activity theory (CHAT; Cole & Engeström, 2006) can be used to theorize, structure, and analyze the co-design process within design-based research. CHAT emphasizes the importance of collective, transformative agency (Engeström, Sannino, & Virkkunen, 2014; Virkkunen, 2006)—the efforts of groups working together to break away from current forms of activity and envision new forms of activity—as the object of design efforts. As we elaborate here, an emphasis on agency requires that learning sciences researchers attend to three aspects of teacher agency in organizing co-design efforts. First, researchers must organize co-design to provide opportunities for teachers to work together to envision and bring about new forms of teaching and learning rather than expecting them to work in isolation from colleagues to do so. Second, it demands that researchers consider how the process helps overcome or mitigate constraints to teachers' professional discretion that derive from historical and ongoing exclusion of teachers from the design of educational innovations and policies (Ormel, Roblin, McKenney, Voogt, & Pieters, 2012). We take up history in design (O'Neill, 2016/this issue, Question 4) not by attending to the particulars of individuals engaged in the process but with the aim of changing institutionalized relations among teachers, administrators, and researchers that give limited authority to teachers in reform. Third, researchers must attend to the ways in which co-design provides specific tools and practices that help teachers break away from current forms of activity in classrooms that limit students' opportunities to learn. Here, we argue, external visions of reform can provide seeds for teams to imagine new possibilities, but CHAT points to the need for tools for helping develop these seeds into new activities.

In this article, we address the following three questions:

1. How can CHAT inform the structuring of collaborative design processes in design-based research?
2. How can teachers shape the content of the design and mitigate effects of constraints from their context through engagement with the projects' tools and routines?
3. In what ways can tools and activities enable teachers to break away from current practice through meaningful engagement with external visions for reform?

Our article begins with a review of relevant CHAT concepts and methods for organizing collaborative design. We follow that review with an analysis of how we applied these concepts and methods to organize the collaborative design of materials that would embody and further develop an external vision for reforming science teaching and learning (Question 1). Then we present an analysis of teacher agency in developing the content of the curriculum materials and proposing changes to the design process itself (Question 2),

highlighting the ways teachers made use of tools and practices that we, the researchers, provided to foster productive engagement with the external vision of reform (Question 3). Finally, we discuss how our research relates to other design-based research in the learning sciences and to CHAT-informed intervention research and how our approach might be applicable to future design-based research.

CHAT AS THEORY AND METHODOLOGY FOR ORGANIZING FOR TEACHER AGENCY

CHAT provides both a theory and methodology for cultivating a "shared problem space" (Akkerman & Bakker, 2011, p. 147) in which people can work together to envision and develop new forms of activity. Working together is important, because solutions to educational problems require diverse forms of expertise. A CHAT approach calls for organizing design efforts so that the expertise of one group is not privileged over another and the opportunity to surface potentially fruitful contradictions increases (Gutiérrez, Rymes, & Larson, 1995; Severance, Leary, & Johnson, 2014). Doing this can increase the effectiveness of design teams (Page, 2007). But effectiveness is not the only aim of design within a CHAT approach. A CHAT approach calls for creating conditions in which groups gain new authority to shape the course of reform and ability to exercise discretion as they move from outsiders to full participants with a stake in defining the object of design (Virkkunen, 2006).

Creating such conditions is not easy within contemporary schooling, because teachers typically have little say over the course of reforms and limited discretion as professionals to shape their own practice in collaboration with colleagues. In contemporary schooling, engaging teachers in collaborative design directly challenges the predominant division of labor, in which policymakers, professional curriculum developers, publishers, and sometimes researchers hold the greatest influence over the design of adopted curriculum materials (Atkin & Black, 2003; Ingersoll, 2003; Tyack & Cuban, 1995). In the current division of labor, teachers have a limited role in design, primarily as testers of materials and as actors charged with implementing materials with students in their classroom. This is true even within many design research studies (Ormel et al., 2012). In educational design efforts, teachers' expertise is often devalued as relevant to a reform; the wisdom of practice has a lower status than evidence from research (Bryk et al., 2015). Thus, the organization of the design process itself must take into account the historical inequities that characterize the schools and communities where designs will be developed and tested (Bang et al., 2010; Penuel et al., 2004).

The approach also demands that researcher-interventionists create conditions for the emergence of what CHAT researchers refer to as *transformative agency*

(Engeström et al., 2014; Virkkunen, 2006). Transformative agency is collective action both to break away from current forms of activity and to develop "new concepts that may be used in other settings as frames for the design of locally appropriate new solutions" (Engeström, 2011, p. 606). The aim of intervention is not to help individuals change in relation to static, unchanging forms of activity. Instead, it is to bring about new *activity systems*, that is, new relations among the components of human activity, including its tools or artifacts, rules, and division of labor (Engeström, 1987, 2011; Engeström et al., 2014). Furthermore, CHAT asks design researchers to consider implementation not as a phase that follows design but as an integral aspect of it (Engeström, 2009).

This stance contrasts with typical ways in which teachers' responses to external reforms are interpreted. In most reform activity, the resistance of teachers is seen as a problem, but in CHAT intervention, resistance is a valued resource (Sannino, 2010). Even when teachers' individual resistance to change focuses on individual problems but not the larger systemic context that creates them, explicitly discussing such resistance can be an important first step in making the development of new forms of activity a "personally meaningful object" (Virkkunen, 2006, p. 52). Co-design must seek to go beyond such acts of resistance, though, in enabling teachers themselves to engage in "transformative action" (Voogt et al., 2015, p. 262). That is to say, co-design must be organized in such a way as to enable teachers to commit to and engage in actions that reflect personally meaningful goals and that result in new forms of activity in their classrooms.

Accomplishing the aim of creating conditions for working together productively to envision and bring about new forms of activity in schools is a tall order. CHAT points to the central importance of *mediation* in human action. Vygotsky (1987) first highlighted the role of what he called *psychological tools* as means linked to the higher mental functions of directing attention, constructing memories, and solving problems. For him, such tools included signs and systems for creating and transforming meaning: language, gesture, systems for counting, mnemonic devices, mathematical symbol systems, diagrams, maps, drawings, and so forth. The introduction of such tools into the flow of activity both facilitates and transforms object-oriented activity. Next we elaborate on the implications of Vygotsky's method for analyzing the role of tools in mediating human action, the method of double stimulation, as a key conceptual resource for organizing collaborative design using CHAT.

The Method of Double Stimulation: Tools and Routines for Organizing Co-Design

CHAT theorists have always been concerned about how to study and support the efforts of human beings to change their worlds and thereby to change themselves. Vygotsky's (1934/1978) method of double stimulation was an early attempt to

study how experimental subjects made use of available tools in their environment to complete tasks presented to them by experimenters. In this method, Vygotsky would first present a task to the study participant (e.g., "Memorize this series of pictures"). Then, rather than observe how the participant attempted to perform the task on his or her own, Vygotsky would provide the participant with a set of tools that could be used to help solve the task (e.g., a pencil and paper). The task and the means by which it could be solved constituted the two stimuli (Valsiner & van der Veer, 2000; van der Veer, 2008). Vygotsky highlighted the need to focus on what artifacts the participant chose, viewing the experimental subject as "an active agent who selects for his own use whatever objects or tools are available" (van der Veer, 2008, p. 22). He also indicated that the tool selected as the second stimulus should be "neutral," though he did not define what might count as a neutral stimulus other than to say that "when difficulties arise, neutral stimuli take on the function of a sign" (Vygotsky, 1934/1978, p. 74) that is meaningful to the participant as an aid to problem solving.

An adapted form of Vygotsky's methodology of double stimulation guides Engeström and colleagues' (Engeström, 2007; Engeström, 2011; Engeström & Sannino, 2010) approach to formative intervention research, an approach called the *Change Laboratory*. In contrast to the situation in which an experimenter puts a single participant into a position in which a defined problem already exists, in the Change Laboratory the task or first stimulus is something that a group of participants defines collaboratively. As Engeström (2011) wrote, participants "face a problematic and contradictory object, embedded in their vital life activity, which they analyze and expand by constructing a novel concept, the contents of which are not known ahead of time to the researchers" (p. 606). As in Vygotsky's approach, it is the participants who select, adapt, or invent the means of solving the problem. But in the Change Laboratory, there is no ready-made solution that the researcher has devised; rather, "the contents and course of the intervention are subject to negotiation and the shape of the intervention is eventually up to the participants" (p. 606). Intervention facilitators, who are often the researchers, expect that proposals for solutions to problems will be met with resistance, as proposals are always "loaded with affects, hopes, fears, values, and collective intentions" (p. 611). Thus, they are not neutral but rather ambiguous in that they are at first general ideas rather than fully developed concepts with implications for action. In the Change Laboratory, the researcher's role is that of a provocateur and facilitator rather than someone who directs activity toward a solution that has been defined in advance.

Sannino's (2010) analysis of teacher responses to a Change Laboratory she facilitated in an Italian school provides a good example of how contemporary CHAT theorists have applied the method of double stimulation. The principal of the school and a teacher representative asked Sannino to provide professional development on formative and summative assessment. Sannino proposed a

Change Laboratory instead, and the two agreed. In the initial phases of the Change Laboratory, a different focus for the work was established: Teachers found it difficult to manage their classes while conducting the traditional individual oral assessments required of all students. Initially some teachers resisted addressing this problem at all, but eventually "a different way of talking about change emerged, involving the taking of individual and collective initiatives for small-scale changes and innovations" related to student assessment (p. 841). This approach illustrates how conditions can be established through the Change Laboratory for teachers' resistance to external demands of administrators to be taken up productively (as opposed to dismissed or ignored) to imagine new possibilities for action in a school context. It also underscores why CHAT theorists (Sannino, Engeström, & Lemos, 2016/this issue) sometimes refer to the method of double stimulation as a principle for volition and agency, as the volition of teachers is recognized and the agency of teachers expanded through the use of the method.

To date, there has been limited engagement with ways in which the method of double stimulation might be adapted fruitfully to incorporate specific ideas and tools from the learning sciences into the process of collaborative design of curriculum materials. Danish (2014) recently explored how activity theory could be applied to the design of a sequence of instructional activities focused on teaching complex systems, and he proposed that learning theories could be important mediators of the design process. Likewise, Penuel (2014) has proposed that local instructional theories are potentially important tools in design. To date, however, research has not explored how such tools might mediate collaborative design processes or what other tools might be necessary to create the conditions for expanding teacher agency in the ways that CHAT demands. The current study aims to address this gap in the research.

THE CURRENT STUDY

In this section, we describe the design of a collaborative design research project called the *Inquiry Hub* (iHub). This design effort took place within a long-standing research–practice partnership (Coburn, Penuel, & Geil, 2013) that is focused on supporting teachers in developing student-centered approaches to curriculum and teaching. In this particular project of the partnership, a team composed of researchers, district leaders from the Denver Public Schools, and teachers were developing and testing the efficacy of new curriculum materials in science education with funding from the National Science Foundation. We describe first the participants in the design research, then the specific project focus and time span, and finally our methods for studying teacher agency in collaborative design.

Participants

In our project, a total of 16 secondary school science teachers participated in the design process, seven of whom also pilot-tested the curriculum materials we co-designed. Of these 16 secondary school science teachers, 12 participated actively throughout the project. The teachers' level of classroom experience ranged from beginning their second year of teaching to more than 25 years of experience; on average, teachers had 12 years of classroom experience. In addition to the core teacher group, the project had the active engagement of five district-level administrators from the Denver Public Schools curriculum office; six members from community stakeholders such as Denver Parks and Recreation and the U.S. Forest Service; two curriculum writers from the Biological Sciences Curriculum Study (BSCS); six university researchers; and two members from the University Corporation for Atmospheric Research, a large research nonprofit.

Focus and Time Span of the Design Effort

The focus of this particular co-design project was on developing and testing a new unit on ecosystems that addressed performance expectations outlined in the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), a set of standards developed from *A Framework for K-12 Science Education* (National Research Council, 2012). The development process was organized both as an opportunity to produce usable, engaging materials for the classroom and as an opportunity for teachers to learn through developing those materials. In line with our proposed design framework, we organized the design space to promote a more equitable arrangement among participants and to foster ownership of the process by teachers.

The description of the design process within this article focuses on the first year of the effort, which the iHub research team initiated with a weeklong workshop that included teachers, district leaders, curriculum developers, and our research team. The design process continued up and through the initial piloting of the materials by teachers through a series of periodic face-to-face meetings and virtual meetings (via the Web conferencing system Zoom). In all, participants put in more than 100 hr of joint work to design materials for the ecosystems unit. Research assistants, curriculum developers, teachers, and district leaders were all paid for their contributions.

Methods for Studying Teacher Agency in Design

Our approach to analyzing collaborative design is primarily ethnographic, focused on developing an understanding of how participants act together to develop new curriculum materials and make meaning of their participation in

the process. It draws on interpretive perspectives on how people constitute local activity settings and is part of a growing tradition of using ethnographic methods to study design processes in the learning sciences (e.g., Barab, Thomas, Dodge, Squire, & Newell, 2004; Jurow & Shea, 2015). That is, we focus on how it is that people participate in and make sense of their participation in design activities.

We relied on multiple sources of data to construct our account of teacher agency in design. Our primary source of data was a set of ethnographic field notes from observations conducted as part of approximately 20 hr of whole-group collaborative design sessions. Other sources were free-write reflective essays from seven teachers written at the conclusion of the initial design workshop, feedback surveys from 22 teachers as part of embedded critique activities (described in detail later as part of our design process), online surveys completed by 11 teachers at the midway point of the co-design process, and four interviews with teachers at the conclusion of the design cycle. We also reviewed the 37 lessons written by participants to develop interpretations of our co-design process.

CHAT provided the framework we used to analyze these data. We sought to identify evidence of transformative agency in the actions of teachers recorded in our data sources and to characterize when and how transformative agency arose within the design process. Thus, we focused on evidence in the form of actions taken to influence the shape of curricular materials and the design process itself. Specifically, we sought evidence on whether our design approach supported teachers in facilitating a breaking away from earlier patterns of activity, either in terms of realizing in practice the vision of the *Framework* or in terms of remediating historical inequities between researchers and teachers. Accordingly, we focused especially on interactions within the whole group in design meetings, because we sought to document the development and coordination of teachers' collective agency. In our case, we interpret the co-design process as the primary site for collective action. We imagine the systems of activity that are transformed through the actions of participants to entail both those of classrooms, in terms of achieving the vision for science education called for in the *Framework*, and the partnership itself, in terms of achieving a new form of design activity that empowers teachers and privileges their expertise.

HOW WE ORGANIZED FOR TEACHER AGENCY IN THE iHUB

In this section, we describe how we used CHAT to organize the co-design process to expand teacher agency within a reform effort within the iHub project. Our intent in focusing on the design process is to contribute to a more refined theory of collaborative design, to which we return in the concluding section of our article.

The First Stimulus: Presenting the Vision of *A Framework for K-12 Science Education*

In Vygotsky's method of double stimulation, the first stimulus is a task that the researcher presents to a participant to accomplish. In our case, that first stimulus was a vision for the improvement of kindergarten–Grade 12 science education, *A Framework for K-12 Science Education* (National Research Council, 2014), and a charge to design a curriculum unit that embodied its principles. We did not define the content or flow of the unit ahead of time. The participants to whom this vision was presented were the design team teachers. The researchers and district leaders who were part of iHub had decided on this first stimulus ahead of time. We note that this approach departs from how Engeström and Sannino (2010) described their application of Vygotsky's method of double stimulation, because in their approach participants jointly negotiate the object or first stimulus. Our process thus seeks to illustrate how co-design may support teacher agency, even when the initial first stimulus for action is external to the collaborative design team.

During an initial 5-day design workshop, we presented the first stimulus as both an ambitious and ambiguous task: to design a curriculum unit that teachers would want to teach to their students while showing integrity to the vision for improving science education as defined in the *Framework*. Given that the *Framework* is a vision, that is, an image of what science education could be, and not a fully realized system of science education, we sought to create opportunities for teachers to exercise agency and leverage their expertise in creating a functional interpretation of the *Framework* as realized in the form of a tangible curriculum unit. As no one knew the form of the unit ahead of time, participants had the opportunity and challenge of negotiating its shape while showing integrity to the vision of the *Framework*. Thus, we followed this presentation with a series of activities in which the entire team had opportunities to interpret the vision of the *Framework*, participate in learning activities that aligned with the vision, and unpack (Krajcik, Codere, Dahsah, Bayer, & Mun, 2014) specific performance expectations of the NGSS (NGSS Lead States, 2013). Teachers could and did challenge aspects of the vision of the *Framework*, and we made efforts to surface concerns teachers had with different aspects of the vision and with implementing it.

In our initial presentation of the first stimulus, we highlighted several elements of the vision of the *Framework*. The key principles emphasize that children are born investigators, that science is both a body of knowledge and a set of practices for generating knowledge, that student understanding develops over time, and that science education should build on students' interests and experience. The *Framework* articulates a three-dimensional view of science proficiency in which developing understanding of a few disciplinary core ideas is posited to go hand in hand with students' engagement in science and engineering practices and their

making connections to crosscutting concepts across different science domains. The vision of the *Framework* also includes a strong focus on equity and the sources of inequity in American schooling. We emphasized in our presentation that the *Framework* identifies inattention to what motivates and fails to motivate students from different backgrounds as a key source of inequity that led the authors of the *Framework* to call on educators to use a wider range of strategies for "build[ing] on students' interests and backgrounds so as to engage them more meaningfully and support them in sustained learning" (National Research Council, 2012, p. 283).

From our perspective, presenting this vision and task was a prologue and differs from what is typically the first step in formative intervention research, the confrontation of dilemmas and contradictions within and between activity systems. We neither expected nor hoped that teachers would simply accept the vision of science teaching and learning in the *Framework* or their charge to develop materials aligned with it. Rather, we introduced the *Framework* in the same spirit that CHAT intervention research confronts participants with a challenging problem. We intended it as a provocation, and we expected resistance to both the vision and the charge along the way.

Small-Group Structure: A Tool for Leveraging Distributed Expertise in Working Together

To facilitate the leveraging of teachers' expertise, we structured activity to occur in small teams to increase the opportunities for teachers to directly contribute to the design and achieve a more equitable division of labor. Because of the large number of participants and varied experiences of researchers, teachers, curriculum writers from BSCS, and district leaders, we also anticipated that it would be more efficient to create smaller teams.

Teachers self-selected into small groups based on their interests in particular science phenomena that would be explored in the unit. In each group, we sought to ensure that teachers made up at least half the membership of each group, with the rest of the group made up of researchers, curriculum writers from BSCS, members from the University Corporation for Atmospheric Research, and district administrators from the Denver Public Schools. This simple move, we posited, would enable teachers to have much more say in the content of the unit. The authority of how to leverage expertise would become distributed across the design space and allow for a more horizontal arrangement of expertise and the meaningful leveraging of that expertise in the design.

Throughout the course of the design work, small groups worked alternately on their own, in which they decided how to develop lessons for their section while being cognizant of work occurring in other groups, and with the whole team. To facilitate coordination between different teams during the design process,

researchers and district administrators also embedded themselves within each small group. Researchers and administrators intended to absorb the task of organizing small-group work in order to enable teachers, who typically have significant demands on their time during the school year, to be in a better position to focus on their ideas for the unit and to take the lead on developing lessons.

The *Storyline* Tool: A Second Stimulus Supporting Organizing for Agency

Because the *Framework* provides a vision rather than a detailed map to support new ways of promoting science teaching and learning, we needed other mediating tools and processes to interpret the *Framework* and for designing specific instructional resources. A key tool we used throughout our collective design work was the *Storyline*, developed by Reiser (2014). Reiser developed the *Storyline* tool to support the development of coherent, well-sequenced units as called for in the *Framework*, that is, a curriculum unit that is "logically organized, integrated, and harmonious in its internal structure" (National Research Council, 2012, p. 245). The *Storyline* tool also attempts to embody principles for project-based learning derived from decades of design research on science curricula, including such principles as driving questions that provide a structure for a sequence of student activities and engagement of students in authentic practices of the disciplines (Blumenfeld, Soloway, Marx, Guzdial, & Palincsar, 1991; Krajcik & Blumenfeld, 2006; Marx, Blumenfeld, Krajcik, & Soloway, 1997; Polman, 2000).

It is important to note that this was the first time the *Storyline* tool had been used to design curriculum. It was developed from Reiser's involvement in design-based research efforts to develop coherent science curriculum units organized around driving questions. As a tool for designing curriculum units that embodied the principles of the *Framework*, it was untested.

The key elements (depicted in Figure 1) of the *Storyline* tool are a series of components that design teams are to complete prior to developing individual lessons. The tool is intended not just to help organize the flow of instructional activities into a coherent whole but also to ensure that students are engaged in science practices to figure out things that can help them answer the unit's driving question or to solve its overarching design challenge.

In our initial design workshop, we proposed using the *Storyline* tool as a means of promoting coherence for the ecosystems unit overall as well as for subparts of the unit. We proposed using it for subparts because we believed that our team was too large to develop lessons as a committee of the whole, and yet we were concerned that each part should have a logical flow and connect with the overall storyline for the unit.

Note that the structure of the *Storyline* tool embodies the characteristics of a secondary stimulus, and we sought to leverage it within the design process to

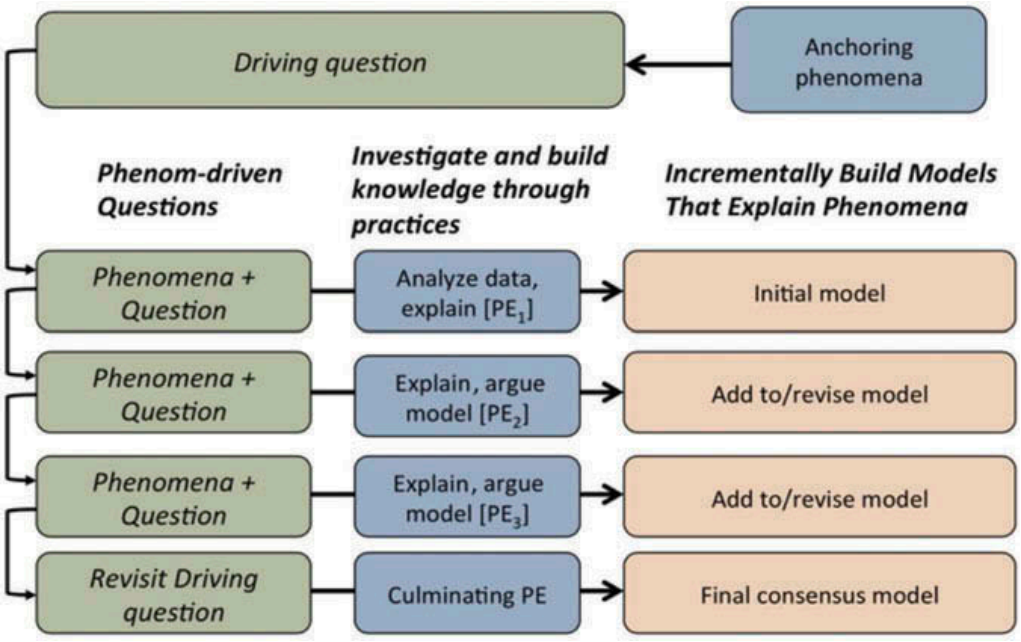

FIGURE 1 Blank *Storyline* tool (from Reiser, 2014). PE = performance expectation.

promote teachers' agency as such. Like any tool, the *Storyline* tool has an expertise embedded in its structure that facilitates the completion of tasks. In this case, the structure of the *Storyline* reflects the *Framework* and research on science curricula, and it serves to facilitate design work. The *Storyline* tool, however, still has a "skeletal" (Engeström, 2011, p. 621) structure and has an inherent ambiguity in that it does not come fully formed or prefilled for use in the design space. Instead, participants in the design space must decide how to fill in the *Storyline* tool and how to imbue it with their own meanings as they pursue the object of design (i.e., a new unit embodying the vision of the *Framework*). It invites participants to decide on the science phenomenon and driving question that will anchor a unit and that students will investigate, the specific science practices in which students will engage, and the particular components of a performance expectation (related to a "Standard") that will be addressed. Teachers must leverage their own unique classroom and content expertise in completing this tool. Doing so may increase teachers' agency, as they have increased their own capacity to influence the design of materials by bringing additional expertise—their own—to the design.

Critique Routine: A Tool for Coordinating Expertise

We also integrated structured critique routines into the collaborative design space. Purposefully seeking to better leverage teachers' expertise and foreground their voices in the design space, we sought to develop routines for fostering critique and design for teachers to have the opportunity to take on an empowered role—that of an evaluator or critic of the emerging design. We also designed these routines to be taken up by participants in ways that could serve as a mechanism for coordinating the work across the small groups.

These critique routines included two structured feedback events. These events required each group to present the lessons they had developed for the ecosystems unit. Other teams in attendance, as well as other participants from community stakeholder groups (e.g., Denver Parks and Recreation), would then provide immediate feedback during whole-group discussions. We also used in-session surveys to promote equitable participation so that all participants could have the opportunity to provide feedback regardless of their level of participation in discussions. In addition to integrating the structured critique events, the research team also distributed online feedback surveys to teachers at key junctures throughout the design process, namely, immediately after starting the design process, midway through the design process, and prior to the piloting of the curriculum. In this way, we could collect and respond to targeted concerns from teachers in a timely manner.

ANALYSIS OF TEACHER AGENCY

In the previous sections, we described our approach to organizing the design space so as to promote teachers' agency using specific tools, routines, and structures. In this section, we present an analysis of how those teachers engaged with these elements of our design approach. Our aim in this section is to examine whether, and to what degree, teachers exercised agency in the design process. Our method of analysis centers on identifying evidence of transformative agency, in other words, instances of a breaking away from previous patterns of activity to achieve new forms of activity, hopefully forms that were valued by participants. On the basis of this analysis, we make two claims: (a) The design process occasioned teachers' agency around the structure and content of the curricular materials, resulting in significant and lasting changes to curricular materials; and (b) the design process occasioned teachers' agency around the structure of the design process itself, resulting in significant and lasting changes to the design process. To support these two claims, we present our analysis as a series of claims accompanied by data presented in narratives we have constructed of the

design process to allow the reader to judge the significance of the changes observed and the mechanisms that we propose account for their occurrence.

Evidence of Agency in Determining the Structure and Content of Curricular Materials

In seeking to move toward the externally provided object of the vision for science education called for in the *Framework*, teachers' actions shaped the structure and content of the ecosystems unit. Specifically, teachers played an integral role in the selection of the anchoring phenomenon and driving questions that provided an overarching structure for the unit; teachers, working in small groups, determined the content and shape of individual lessons; and teachers leveraged ideational tools such as the notion of coherence and moving beyond "trust me science" when evaluating curricular materials. Together, these informed changes in the unit's structure.

Selection of an Anchoring Phenomenon for the Unit. For the teachers on the design team, both selecting a single curriculum anchor and organizing their own sequence of lessons around that anchor were new planning activities. The teachers on the design team either taught biology using the district's adopted textbook, *BSCS Biology: A Human Approach* (BSCS, 2006), or used materials they found that aligned with individual state standards. Although *BSCS Biology* is grounded in an instructional approach consistent with findings from learning sciences research (Bybee et al., 2006), the text is not organized around a single anchor. Thus, our co-design work was organized to help teachers break away from current routines in the way they interacted with curriculum materials toward a vision more closely resembling that of the *Framework*. Here we provide evidence that shows how teachers and others exercised agency that resulted in choosing a phenomenon to anchor the unit.

Early in our first design workshop, teachers on the team got a chance to use the first part of the *Storyline* tool to make suggestions about and select the anchoring phenomenon for the ecosystems unit. The first step in this process was a whole-group brainstorm of possible anchors for the unit facilitated by the second author. Teachers began sharing both possible phenomena and driving questions. The first offered by a teacher was a driving question: "Why can't you drink water from the Platte River?" Another suggested focusing on the question "What's killing the trees?" This question referred to the devastating impact of the mountain pine beetle on native lodgepole pine forests. Other teachers suggested "Why do animals go extinct?" and "How does dog poop affect our community?" The latter question prompted participants to acknowledge that phenomena that occur in urban ecology settings should be preferred over those that occur in

mountain ecology settings, for as one teacher commented, "Right, we don't have mountains." Teachers (with facilitators pushing for specificity) suggested more location-based, urban ecology phenomena, such as "How does development affect prairie dogs?" Following a teacher's suggestion of "How do trees in the world affect me?" the first author suggested, citing a local tree planting initiative, "Why should I plant a tree in my neighborhood?"

Following the brainstorming session, the design team broke into three separate groups to dig deeper into aspects they would need to consider in selecting a phenomenon. One group analyzed the NGSS science and engineering practices related to the performance expectations for ecosystems in the NGSS in order to get a sense of what the NGSS expects students should have the capacity to demonstrate at the end of the unit. Another group focused on student interests and connections, specifically, what sort of phenomena and questions students would find engaging. The final group examined educational research pertaining to impediments students typically encounter when learning about ecosystems concepts. After small groups worked on their respective tasks, facilitators then reformulated groups so that each new group had members from the previous three, allowing each group to have access to the expertise of the previous groups. Each of these new groups then engaged in developing an argument for which two phenomena—chosen from those brainstormed previously as a whole group—they believed would provide the most ideal means of anchoring the ecosystems unit.

Each group presented its proposals to the whole group for review, which led to participants engaging in discussions of whether phenomena/questions should anchor the unit and what such a unit would entail. A teacher from the first group presented a single proposal, the "planting of trees, the ecological issues that surround tree planting," an endorsement of the question "Why should I plant a tree in my neighborhood?" from the brainstorm. The teacher also shared the driving question for this phenomenon: "If you plant a tree, one tree, themselves, will it make a difference?" A teacher from this group suggested that the phenomenon could be "Denver advertises that they give away free trees." The lead facilitator responded, "Is that a scientific phenomenon to be explained though?" Seeking to provide support that some form of the phenomenon actually could serve as a scientific phenomenon, participants from the second group—who had also selected this same phenomenon/question—shared part of a report a teacher in their group had found of how tree cover correlates positively with the health of an ecosystem and how "if Denver increased its tree cover by 25% the environmental and economic effects would be substantial." Intrigued by the idea, but wanting to know more, another teacher questioned, "So, what is 'substantial'? What are the 'economic effects'? What are the 'environmental impacts'?"

The group continued to engage the possibility of focusing on the role of tree planting and tree cover, proposing different ways to word a driving question for the unit that highlighted different aspects of this potential phenomenon. A district

administrator suggested, "I see a new neighborhood of houses going in, they're taking away all the trees, is that a good thing?" This spurred the lead facilitator to rephrase the district administrator's rephrasing of the phenomenon as "A change brought about by humans in the local ecology has an impact on the ecosystem." Pointing to the group's presentation, the facilitator declared, "This is our way in, to explore almost the reverse of that." Not challenging this rephrasing, a teacher in the first group made the case that the exploration of the proposed phenomenon could touch on numerous disciplinary core ideas. In addition, this teacher also suggested a culminating project of "urban planning, pulling in some engineering," in which students could "design something" in their communities.

Like the first group, the second group had also chosen, independently, the phenomenon/question relating to tree planting. Echoing the teacher's comments from the first group about "urban planning," this group suggested that the phenomenon be an engineering challenge focused on "designing a solution" to a real problem. In presenting their proposal, a teacher explained that they focused on envisioning:

> If I was a student, what would I need to know about. Why should I plant the tree? Where should I plant the tree? How close to other trees should I plant it? In what area should I plant it? … Denver gives you a tree to plant. What do you do?

This group also sought to have students examine the impact of planting trees "on a local, global scale." Other participants seemed encouraged by this approach, which one of the researchers labeled a "design-centered" phenomenon. This researcher saw possibilities in having students examine evidence in the report a teacher in the group had found that had spurred their design-centered tree planting proposal.

The second author then asked the group, "Do people see the possibility of blending these two ideas into a single one?" Several teachers provided their opinions on how the two proposals could complement one another, with most seeing the design-centered approach of the second group as providing a motivating challenge for students within which the specificity to disciplinary core ideas of the first group could become embedded.

The third group to present chose a different phenomenon/question from the previous two groups for its proposal. A teacher from the third group began their presentation by sharing their phenomenon, "Wild animals are seen in the city"—which specifically built on a phenomenon/question from the brainstorm on the presence of foxes in cities—and shared their driving question, "Why are they there?" Reiser then explicated a partially completed *Storyline* representation using their chosen phenomenon as an anchor. During this presentation, participants from other groups sought to find opportunities for integrating and building on ideas presented in this group with other groups. For example, one teacher from the

second group, pointing to the third group's *Storyline* representation, offered, "I actually think that, if we're combining the two tree ideas, that the one we built, our flow diagram has a lot of those questions that we just need to put in."

The group deliberated next about the merits of having one or two different units, each with a different anchoring phenomenon. Different teachers voiced different ideas, with some arguing that two phenomena would sustain student interest better than one while others worried that there would not be enough time to teach two units. At an impasse, facilitators split participants into two groups, with each developing a culminating performance assessment for one of the two possible phenomena/questions. After presenting their work back to the whole group, the lead facilitator said that whatever challenge they picked would need to anchor the whole unit, and so the group would need to pick one to move forward. Initially the lead facilitator asked for participants to come back the next day to make their final arguments, but a teacher instead insisted that "I don't think we need to argue … none of us are married to foxes." Checking with other participants, the lead facilitator asked, "So, I'm hearing trees?" No participants voiced disapproval to the motion. "Okay, let's go for it," said the facilitator.

Although the exact language of the phenomenon shifted over the course of the next several weeks to "Humans modify their ecosystems through the practice of tree planting," the main kernel of the phenomenon/question that the participants agreed to at this initial design workshop did become the permanent anchor for the ecosystems unit. In addition, the idea of having students "design something," to engineer their urban environment, as suggested by the teacher in the first group and which served as the structure of the second group's approach, also was taken up permanently in the unit. Specifically, this element became the driving question for the unit's design challenge, in which students would figure out *What tree should we plant and where to maintain the services our ecosystem provides?*

This extended episode demonstrates how teachers' agency influenced the selection of both the anchoring phenomenon and driving question for the unit. It shows how teachers took action toward organizing the unit around an anchoring phenomenon and driving question, an orientation aligned to the vision of science education in the *Framework*. We also see in this example how agentic acts can interlock and build on one another. This interlocking process of agentic acts proved common during the design workshop and demonstrated the importance of having teachers' agency as a link in the chain. In addition, we see here how participants engaged with elements of our design process (e.g., small groupings, critique sessions, the *Storyline* tool), both separately and in combination, to move the design forward.

Teacher Teams' Determination of the Content and Flow of Individual Lessons. Teachers not only decided on the overall anchor for the unit but also determined the content of individual lessons as well as the flow of those lessons. Here we provide evidence that demonstrates how teachers, within their small groups and through the taking up of other elements of our design approach, exercised agency to shape the content and flow of individual lessons.

Toward the end of the initial 5-day design workshop, the facilitators asked participants to form small groups that would each commit to developing lessons for one of the four subquestions within the *Storyline* diagram. Each of the four groups consisted of two or three teachers and one or two group facilitators, who were either researchers or curriculum specialists at the district. Before leaving the workshop, facilitators tasked each group with completing a "team charter," a collective agreement among group members over how to divide up the labor of creating the lessons relating to their subquestion and a schedule their work would adhere to. Over the next 5 months, the groups met regularly to develop the individual lessons that would eventually compose the ecosystems unit.

In developing their lessons, individual groups continued to use the *Storyline* tool developed at the 5-day workshop to organize their own work and coordinate with the work of other groups. Each team was responsible for elaborating on lessons related to a row or subquestion of which they took ownership (see Figure 1), yet each group still had to determine (a) which science and engineering practices students would use in order to explore their particular subquestion; and (b) what understandings of disciplinary core ideas students would build around their subquestion that would lead naturally to the next row and subquestion in the *Storyline* diagram or, in the case of the final group, would lead to a culmination of the unit. Initially, each group worked independently to figure out how to organize a sequence of lessons lasting roughly 2 weeks.

A close analysis of one group's efforts illustrates the ways in which teachers exercised agency in small groups to influence the content and flow of individual lessons. This group was referred to as "Group 4" because its task was to develop the last of four parts of the unit. Initial work within this group focused primarily on determining how to effectively fill in its assigned row in the *Storyline* diagram. The group members believed that doing so would ideally provide them with a clearer idea of how to develop actual lessons that engage students in using science and engineering practices to explore their subquestion and build relevant pieces of the disciplinary core ideas and crosscutting concepts. Much of the design work at this stage in Group 4, therefore, consisted of proposing and evaluating lesson ideas. For example, one teacher had proposed using existing materials to create a lead-in lesson looking at how humans can negatively impact the services ocean ecosystems provide. Another teacher questioned whether such a lesson fit coherently within the group's section and the unit. Compromising, the

teachers decided that the lead-in lesson would need to address forestry and tree ecosystem resources more directly.

After evaluating and critiquing potential approaches for their lessons and deciding on what they believed would be the most viable ideas, members of Group 4 began to consolidate their ideas and record them within the *Storyline* tool. Doing so required members of Group 4 to reach agreement on numerous aspects of the lessons, such as the content and instructional approaches the lessons would use. For example, teachers had to agree on the format of the final culminating product students would produce, as the product provided students with a common thread throughout all of the lessons in this section. Teachers agreed that the final product would require students to work in small groups from start to finish (rather than work individually) and that students would present their conclusion about what tree to plant to the class (rather than simply submit a report to the teacher). Each group, the teachers decided, would have to make an argument for how planting a specific species of tree in a specific location would best maintain the services and stability of the urban ecosystem. Referencing the *Storyline* tool and the NGSS, the teachers felt that such an approach would require students to engage meaningfully in science and engineering practices, in this case, engaging in argumentation from evidence to explore and leverage disciplinary core ideas students had developed throughout the unit.

With a draft of their row in the *Storyline* tool complete, members of Group 4 then went about the work of actually bringing their collective vision for their section of the unit into being. After negotiating what would constitute a fair but realistic workload among the group members, each member agreed to write a sequence of two or three lessons. This approach, teachers felt, would also best maintain coherence across lessons, with set chunks of lessons coming primarily from the same lead authors. Using a common lesson plan and slide template, each member slowly developed lesson materials for classroom implementation. At scheduled time periods, members of Group 4 reconvened to share their progress with one another and evaluate one another's work. At one such meeting, a teacher floated the idea of having students collect field evidence necessary for making their final argument digitally using their phones rather than using more traditional paper-based field notes. This idea gained traction and became reality after further collaborations between Group 4 members and computer scientists at the University Corporation for Atmospheric Research. Teachers showed palpable excitement at the development of a technological tool for recording evidence students would need to support their argument, with one teacher commenting, "I can't believe they actually made it. It's real." Teachers felt that utilizing technology in this way to collect data would allow students to have a deeper engagement with science and engineering practices such as developing and using models.

Not all groups structured participation in the same way as Group 4 did to allow teachers to lead the writing of lessons. Although members of Group 4 negotiated a

division of labor that they deemed an equitable distribution of the workload, with teachers taking the lead authorship of chunks of lessons, other groups did not do so. For example, in Group 1, a researcher served as the lead author on six of seven lessons. In Group 3, a curriculum writer from BSCS served as the lead author on six of 11 lessons. Only in Group 2 did teachers serve as lead authors on all seven lessons. In Group 4, teachers contributed the majority of lessons, serving as lead authors on seven of 12 lessons.

This section provides an illustration of how teachers exercised agency that led to lasting effects on the content and flow of individual lessons, but we also provide evidence that their agency in developing lessons varied across groups. At a fundamental level, each group's completion of its lessons provides evidence of tangible attempts to achieve the vision for science education in the *Framework*, yet the variation in teachers' degree of authorship from group to group calls into question the degree to which teachers shaped lessons. In terms of the design process, the small-group structure, in concert with the use of the *Storyline* tool, seemed to facilitate the work of Group 4. Members of Group 4 credited the ability to work out their ideas in a small group and the fact that they were collectively committed to the effort as important factors in their productivity.

Teachers' Appropriation of Content-Related Ideational Tools. In Vygotsky's method of double stimulation, analysis focuses on whether and how participants take up or use tools introduced by the researcher. Here we present a similar type of analysis, focusing on the ways in which teachers took up key ideas introduced as tools for designing coherent units that embodied the three-dimensional vision of science learning presented in *A Framework for K-12 Science Education* (National Research Council, 2012). We found strong evidence of appropriation of two key ideas by teacher participants in ways that we, the members of the research team, could not have anticipated ahead of time.

One of the facilitators introduced both ideas during the second day of the initial 5-day design workshop. The first was a contrast between what he called "trust me science" and giving students the opportunity to "figure out" core science ideas. In trust me science, "the teacher does the lab, then teaches the idea so kids understand what they just saw" (Reiser, 2015, p. 22). By contrast, in figuring out science, the central aim is for students to develop models that explain phenomena rather than just learn about them. The second idea was that of coherence, which is central in *A Framework for K-12 Science Education* and is an aim the *Storyline* tool seeks to support. According to Reiser (2015, p. 25), when lessons are organized into a coherent storyline, "investigations are motivated by questions from phenomena, not [the] order of topics in [a] textbook."

There were multiple examples of teachers taking up the language of and distinction between trust me science and figuring out science. For example, at

the conclusion of the 5-day design workshop, one teacher described what he had learned during the workshop in the following way: "Lessons should be built around students' need to know to make sense of phenomena. We tend to use various less effective teaching strategies, including 'trust me' and 'look at this cool thing!' strategies." Similarly, other teachers saw the notion of trust me science as an important means of making design decisions early on in the design process. One teacher commented at the conclusion of the 5-day design workshop, "We may be veering towards our comfortable zone too much and we need a list of non-negotiables—like the 'trust me' and how to solve that when it comes up." Teachers also drew on ideas related to the notion of trust me science, particularly when evaluating lessons within the unit. For example, during a face-to-face design meeting, Group 2 presented its ideas for its section of the unit to the other groups. Its lessons made heavy use of previously developed materials, particularly a lab that had students collect data on oxygen and carbon levels within a container filled with select organisms. One teacher critiqued the group's lessons, citing that the "activities suggested seem to be 'demonstrations' as opposed to inquiry labs." Although not directly referencing the notion of trust me science, this teacher showed concern that the materials presented placed students in a passive position and did not meet the main goals of the design effort, which this same teacher described as to:

> incorporate NGSS into [the design] which are some higher learning skills and higher kind of inquiry and the idea of having the kids solve the problems and having the kids go out and figure out the learning kind of on their own.

Some participants also took up the second key idea, coherence, as a filter for evaluating the fit of lessons to the anchoring phenomenon. During a face-to-face meeting in the fall at which each group presented in-progress work pertaining to its section in the *Storyline*, for example, teachers leveraged their understanding of the notion of coherence to alter the structure in the *Storyline* and hence the unit itself. While each group presented, members of other groups provided feedback via online surveys. After Group 3 had presented, a teacher commented in the online survey, "I think this section should be before group 2." After the presentation of Group 2, members of Group 3, having read the survey comments they had received, submitted survey comments for Group 2 that showed a taking up of the initial proposal: "It was suggested to group 3 that [group] Q2 and 3 switch order—we think this makes a lot of sense." Group 3 then brought the proposed switch up for discussion with all of the participants present at the meeting, saying, "We think that it makes a lot of sense because we're starting at a very basic level—trees need sunlight, nutrients, and, but they've already done the carbon cycle." A teacher from Group 3 continued, "And it would help you guys

[points to Group 2] 'cause then we've introduced trees need water and sun, and then it's an easier, like, 'Oh and this is why.'"

In this sequence of interactions, however, decisions about phenomena were not motivated by questions students might have, as the *Storyline* was intended to support. Rather, the sequence was ordered according to teachers' hypotheses about what concepts would build on one another or be necessary for subsequent lessons. In this respect, teachers' uptake of the notion of coherence was not as the researchers had predicted.

Furthermore, only some of the groups took up these ideas as resources for determining the content of their section of the unit. For example, although members of Group 2 had received feedback from other groups around the need to revise their lessons so that they more coherently connected back to the anchoring phenomenon and allowed students more opportunities to figure out phenomena, some of their final lessons still did not fully reflect these design ideals. One lesson in particular stood out as having students simply learn about phenomena. Instead of exploring an observable subquestion that clearly related to the engineering design challenge or anchoring phenomenon by engaging with science and engineering practice, students completed a reading to answer the teacher-supplied question "Where does the mass of trees come from?"

This section demonstrates how teachers engaged with ideational tools during our design process and exercised agency in leveraging them within the design process. Although we saw uptake of the distinction between trust me science and figuring out science, and the virtue of coherence in curriculum design, the appropriation of these ideas was uneven across the teachers and groups. That we saw demonstrations of partial appropriation occur within the context of participants closely engaging with elements of our design process suggests that our design approach may continually elicit these ideational tools. Despite only partially appropriating the ideational tools, teachers nonetheless exercised agency in their use, which resulted in lasting changes to the unit and its lessons.

Evidence of Agency in Reshaping the Design Process

Teachers not only selected the content of the units, they also appropriated, to different degrees, key ideas from the researchers and proposed changes to the design processes that challenged how we, the researchers, had organized that process. As described next, the teachers, working in small groups, exercised agency in ways that led to the development of new in-between tools to support more effective design; teachers, working in small groups, utilized critique routines to provide critical feedback on the variability of groups' progress on generating lesson materials, which prompted changes in group structures; and teachers, through surveys embedded in critique routines, provided feedback that led us to shift the structure of co-design sessions to accommodate their critiques of the process.

The Development of New Tools to Support the Design Process. Teachers working in small groups developed alternative means of designing lessons in response to perceived limitations in the tools we had provided them. Although the *Storyline* tool proved to have a constant presence throughout the entirety of the design process, shifting in form as deemed appropriate by participants, its ubiquity did not always translate into utility. Here we provide evidence for how teachers, within their small groups, demonstrated transformative agency in their creation of in-between tools that served to alter their own design activity.

In introducing the *Storyline* tool at the 5-day design workshop, the facilitators had intended to support a deeper understanding of the notion of coherence and provide participants with a common tool for organizing the creation of a more coherent unit anchored around explaining an overarching phenomenon through the exploration of related subphenomena. At this high level of granularity, the *Storyline* tool served well as a means of coordinating high-level elements of the unit in relation to one another. Issues began to arise, however, during small-group work when teachers and their group facilitators had the task of developing actual lesson materials for rows of the *Storyline* tool, as illustrated by an examination of work that occurred within Group 4.

Participants in Group 4 sought to develop an in-between tool to bridge the gap between the *Storyline* tool and a lesson plan template developed by district administrators and researchers. They desired a tool that better articulated pacing and lesson length. Within their small group, members of Group 4 had criticized the *Storyline* tool as providing too little support in determining much-needed information such as whether all of the elements listed in a row would actually fit in the allotted time. In response, members of Group 4 developed an in-between tool to re-represent the information in their row of the *Storyline* in a format more familiar to teachers and closer to the final format of actual lesson materials, a simple table that described the topics of each lesson and prescribed the number of days each lesson would encompass. Group 4's envisioning and development of this in-between tool enabled it to engage in more consequential design work. For example, from their in-between tool the participants now had a clearer sense of the purpose and flow of each lesson, their implementation time, and topics each lesson would require or the density of each lesson. This allowed members of Group 4 to divide up coherent sets of lessons among group members in an equitable manner and provided much-desired concrete boundaries for each lesson writer to work within.

Following a previously seen pattern of participants' agentic acts interlocking and building on one another, this section provides an example of teachers exercising agency to develop a tool that altered their own design activity. Specifically, in taking a neutral, skeletal artifact—a table—and filling it with meaning, members of Group 4 provided a classical example of agency through the method of double stimulation. They took up and completed the second

stimuli of the table in order to address the immediate problem or first stimulus of creating lesson materials, resulting in an enhanced capacity to pursue the design and development of lesson materials.

Teacher Criticism of Variability in Groups' Productivity. In a series of actions that likely reflected a growing sense of ownership over the design process, teacher participants exercised transformative forms of agency almost exclusively through the critique routines provided as part of our design process that led to changes in the participant structure of a small group. We provide evidence here for how teachers exercised agency in contributing to this significant change in the design process.

Although three of the four groups that formed during the conclusion of the 5-day design workshop developed and executed effective plans for going about the work of developing their lesson materials over the following months, one group —Group 2—experienced less success and productivity in developing its lesson materials. In contrast to the other three groups, Group 2 did not complete a team charter, which would have required them to negotiate a strategy for achieving the task of developing tangible lesson materials in the months following the workshop. Instead, the lead facilitator for the group, Mary (a pseudonym), took on the writing of lesson plans herself. A teacher within the group later lamented, "I left the summer with the understanding that Mary wanted to take on all of the lesson writing for our group, so I didn't do any work over the summer. I wish now that I had." After a face-to-face meeting in which Group 2 presented only sparse materials in comparison to other groups, the members of other groups provided feedback to researchers and administrators expressing their displeasure with Group 2's lack of progress. For example, one teacher offered through a survey, "Those who aren't getting their work done clearly don't value the project, nor the other people who are counting on them." Other teachers proved more vociferous in their criticisms of Group 2, with one teacher commenting through a survey,

> Why is it that we have a group that came to the table more than once without any project complete? We all joined this group knowing what needed to be done, and what we had to do. Group 2 had come to the table MORE THAN ONCE with NOTHING!!!… The fact that their last presentation of what they have is simply lessons that they have borrowed from someone else is disgusting. It has created a [*sic*] understory of resentment and discontent.

The lack of progress displayed by Group 2 prompted interventions from the researchers and district leaders. We added two additional teachers to Group 2 to buoy their ranks. Even then, they still ran into challenges self-organizing productively. For example, in responding to a survey prompt of what concerns she had, one of the new teachers who had joined the group 2 months prior reported,

"We are just behind so all of my concerns have been addressed we just need to get some work done. We are meeting next Saturday so we should feel caught up by then." With hard deadlines for submitting an initial draft of the unit to external reviewers fast approaching, researchers and district administrators decided to bring in an additional facilitator for Group 2 to support the lead facilitator in organizing and executing their work. This decision paid off, as Group 2's productivity recovered and it delivered tangible lesson materials for the review.

In this section, we sought to demonstrate how teachers utilized elements of our design process, chiefly critique routines, to precipitate a change in the structure of a small group. Although the manner in which participants' agency culminated in these changes followed an interlocking pattern of agentic acts, this example provides a slightly different flavor in that although teachers first exercised agency using elements of the design process, the researchers and administrators ultimately exercised their own agency in carrying out the change to the small group. The fact that the researchers and administrators ultimately held and exercised the agency that resulted in a change in the design process raises questions about the degree to which divisions of labor in our design approach may constrain the agency of teachers.

Recommending Shifts in the Structure of Collaborative Design Sessions. The most significant changes to the design process brought about by teachers' exercise of transformative forms of agency dealt with shifts to the structure of the collaborative design sessions. In this section, we provide evidence for how teachers exercised agency that led to fundamental shifts in the structure of joint co-design sessions. Teachers provided, but also went beyond, criticism to make concrete proposals for organizing the co-design process to be more productive and satisfying to them. Their proposals, as we elaborate here, called for more collaborative, face-to-face work among the teachers so that they could engage more deeply with the ideas they were discussing and rely more on one another to develop lessons.

After the intensive 5-day design workshop held during the summer, the structure of whole-group design work shifted to other formats during the late summer and into the school year, which some teachers criticized and sought to change. Teachers expressed concerns over the structure and effectiveness of regular, hour-long videoconference meetings that all participants had attended to discuss their progress. Teachers suggested that the videoconference meetings did not provide the depth of interaction they had experienced in face-to-face meetings. For example, one teacher commented in a survey, "I dont [*sic*] see the Zoom [videoconferencing software] calls as helpful as the face to face meetings." Similarly, another teacher offered, "I think face to face meetings are key—it is tough to work virtually. I have found that quality of the work we produce after face to face meetings is much greater than after

virtual work." Teachers cited the lack of "big blocks of time together" as a key limitation of the work format during the school year, with one teacher even suggesting that the format of "stretching this 1 unit out into meeting, after meeting, after meeting, has not been conducive to creating a solid product."

Going beyond simply offering criticism, several teachers provided very similar potential remedies either for how to address the ineffectiveness they specifically perceived in the work format implemented by researchers and administrators during the school year or for how to generally improve the design process. Of the 11 teacher participants, six suggested through their survey responses the need to alter the design process so that participants would engage in more face-to-face, intensive design sessions occurring over what one teacher envisioned as "continuous blocks of time." More specifically, four of these six participants suggested that such work should occur exclusively during the summer months. For example, one teacher offered the following:

> I propose more similar time like we had in Boulder, short, sweet and intense. I do not think I can commit to this project if the rest is to be completed during the school year. It has actually created resentment (others have said the same to me) toward the project for eating into the little time that we have during the school year.

The suggestion of moving the bulk of design work outside of the school year to the summer serves as a prominent instance of teachers' agency leading to a substantial shift in the overall design process. Subsequent design work, in which teachers engaged in revisions of the ecosystems unit and developed new biology units, made use of the design format teachers first suggested here, although some design work still had to occur during the school year.

This section described how teachers exercised agency to achieve a new form of activity in the design process, namely, a new structure for joint collaborative design sessions. Similar to the instance regarding criticism of Group 2 discussed previously, teachers utilized almost exclusively the elements of our design approach, such as the surveys embedded within critique routines, in exercising their agency. However, once again, this example demonstrates an imbalance in agency between teachers on one side and researchers and administrators on the other: The division of labor ultimately placed the agency to make the structural changes suggested by teachers in the hands of researchers and administrators. In addition, researchers and administrators did not fully implement the suggestions made by teachers.

DISCUSSION

Our article illustrates one way that CHAT can inform both the organization of a collaborative design process and an analysis of its effects. In terms of O'Neill's

(2016/this issue) first question about what a CHAT perspective buys us, CHAT foregrounded in our design approach the importance of promoting teacher agency as an object of design, and it provided us with a method (double stimulation) for introducing tools and routines that could facilitate the development of curriculum materials to embody an external vision of how to reform science education. It also provided us with a lens for judging the success of our efforts: specifically, whether the agency of teachers proved transformative and led to new forms of activity (Engeström et al., 2014; Virkkunen, 2006).

By focusing on organizing for agency, we brought to the foreground aspects of the design process that are not always highlighted in accounts of design-based research (Ormel et al., 2012), except among scholars who theorize the role of co-design in supporting teachers' involvement in changing their own instruction (e.g., Voogt et al., 2015). Our description of the co-design process is different from earlier attempts to theorize co-design as a mechanism for promoting teacher learning, however, in that we specified ahead of time how specific tools and routines were intended to serve as a second stimulus to support the work of design teams. In doing so, we hoped to hold ourselves to account for our decisions about how to organize the design process, much as some other learning scientists have advocated with respect to innovation designs (e.g., Sandoval, 2014).

Our approach to analysis, moreover, contrasts with earlier empirical analyses presented retrospectively, and mostly in first-person accounts of the co-design process from researchers (e.g., Kwon et al., 2014), which are subject to retrospective reorganizing of accounts, and from analyses that focus on teachers' experience of the co-design process (e.g., Penuel et al., 2007) rather than on the actual recorded actions of participants. In addition, in attending carefully to acts of resistance by teachers in the design process as a form of agency (see Engeström et al., 2014), we gained awareness of ways in which teachers influenced not only the new curriculum's content but also the design process itself. Finally, our detailed analysis of interaction revealed specific examples of how valuable contributions from teachers and other participants did not originate from any one individual but instead occurred through intricate interlocking agentic processes of participants taking up and building on the ideas of others.

As noted at the outset, because we began with an external vision for reforming science teaching and learning, our approach was different from other CHAT-inspired intervention research, which positions implementers as the primary if not sole source of ideas for addressing problems of practice. Our research team, supported by district administrators, provided second stimuli that were more ambiguous than neutral—that is, they were directed to realize particular aims for transforming teaching and learning activity in classrooms, even if these tools did not dictate the focal phenomenon of the unit or the content of specific lessons. In this respect, it is our view that CHAT alone was insufficient to guide design; we needed to bring in specific concepts and tools developed as

part of other traditions of design-based research in the learning sciences to accomplish our aims. The researchers, moreover, contributed in an ongoing way to the development of lessons, serving as primary authors of more than one third of the lessons in the unit. Thus, to answer the question of "Who does the design and why?", the "who" is a bit different in our work than the answer for other CHAT intervention research projects. The answer is that "we" do the design, in which the "we" encompasses teachers, researchers, curriculum developers, and district administrators.

These differences from CHAT intervention research, as well as the counter-evidence we developed related to teacher agency, underscore to us the ways in which our own co-design process was not fully democratic (see also Penuel et al., 2007). The researchers and district leaders held the power for deciding how to structure the design process and for selecting which tools and routines to use as second stimuli in the process. We also were responsible for selecting the teachers who participated in design and for managing the funds to pay teachers. In addition, by imposing an external vision for reform on the design process, we constrained possibilities for breaking away from current patterns of activity and from the current division of labor between district leaders and teachers. The external object, fortunately, was one that was itself ambiguous and underspecified, leaving room for teachers to design curriculum materials that they believed would engage their students and result in more powerful learning experiences for them.

One reason why we were not fully democratic in our process pertains to the expectations of funders. Funding for our project came to the researchers from the National Science Foundation, and through the process of peer review, our project's plan to co-design materials was judged to have sufficient intellectual merit and potential for broader impacts to warrant a recommendation for funding. At the same time, this agency, like others, holds the researchers accountable for the outcomes of the project. We took that responsibility seriously, in that we sought to make sure that the designs we created were innovations that built on past research and had potential to be transformative, a key criterion that the funder uses to judge the merit of projects. We therefore maintained decision-making power for the overall direction of the project, despite our commitments to supporting teacher agency in design. For us, the question of how to preserve latitude with funders who have committed to partly defined goals raised by O'Neill (2016/this issue, Question 2) remains challenging, because whenever funding goes to researchers and not to partnerships that share equally in decision making, it is not possible to implement fully democratic design processes.

CONCLUSION

In this article, we have described how CHAT informed our organization of a design space in which we sought to promote the agency of teachers as they

engaged, via co-design, in the development of curricular materials meant to embody the vision for science education called for in the *Framework*. CHAT drew our attention to the need to organize the design process and place agency with teachers as a fundamental desired outcome (Engeström, 2011). Specifically, CHAT oriented us to seek to foster forms of transformative agency, defined as a joint effort to envision and bring about new forms of activity, to break away from older patterns of activity (Virkkunen, 2006). As in many other design-based research projects, we intended the objects to be used by students and teachers in classroom settings. In our project, however, we focused our attention on the organization of the design space in which participants developed such objects (e.g., curricula). We did so because of our interest in promoting transformative forms of agency that could lead to a new form of activity in curricular design spaces, one that confronts the traditional division of labor that defines policymakers and researchers as designers while positioning teachers as only the implementers of policies, programs, and practices.

We have provided evidence that the collaborative design of materials can be organized to promote teachers' agency and enable them to productively leverage their expertise when the vision for reform is external but not completely specified ahead of time. While seeking to develop curricular materials embodying an external vision for reforming science education, teachers in this project enacted agency through engagement with elements of our design process. When teachers exercised forms of transformative agency, they significantly shaped both the content of new curriculum materials and the design process itself. Our study has further illustrated how substantial contributions can come about from participants building on the contributions of others in collective design activity. In several cases, these contributions were creative and innovative. Together, we also figured out—partly through trying different second stimuli—better and more varied means of supporting the development of coherent curriculum materials by listening to and responding to teachers' concerns about the design process.

When researchers bring to the design process an external vision for improving teaching and learning, the kinds of theories of disciplinary learning and pedagogical design that design researchers in the learning sciences have developed in the past can suggest what might be appropriate second stimuli in design. Such tools may be useful to teams, when presented as "principled practical knowledge" (Bereiter, 2014) derived from past research. As Engeström (2011) reminded, however, it is important to take care that the external visions presented to participants as second stimuli do not become mechanisms of control for and by researchers in design research. Just because something worked elsewhere, elsewhen does not mean that it will work in a new context.

Our own experience and analysis in the iHub has led us to as many questions as answers with respect to how to promote meaningful teacher agency in design. Although our results provide evidence of the power of purposefully promoting

teachers' agency to leverage their expertise in design, several aspects of our curricular materials and changes to our design process relied heavily on the agency of researchers and administrators in order to become enacted. Navigating how to plan for more democratic forms of participation within our research–practice partnership will continue to serve as a focus of future work. In addition, whether the vision of *A Framework for K-12 Science Education* (National Research Council, 2012) can be realized without expanding teachers' agency in significant ways is still an open question, though we are persuaded by past research that suggests that teacher agency is critical for realizing that vision.

More broadly, we see the need for theories of design methodology in the learning sciences to structure collaborative design in ways that simultaneously promote the agency of participants within the design process and expand possibilities for what new forms of activity are possible in classrooms. As we have argued here, CHAT provides an important lens for helping us to design for and analyze agency.

FUNDING

This work was supported by Award No. 1147590 from the National Science Foundation. The opinions expressed herein are our own and do not necessarily reflect those of the National Science Foundation.

REFERENCES

Akkerman, S. F., & Bakker, A. (2011). Boundary crossing and boundary objects. *Review of Educational Research*, *81*(2), 132–169. doi:10.3102/0034654311404435

Allen, C. D., & Penuel, W. R. (2015). Studying teachers' sensemaking to analyze teachers' responses to professional development focused on new standards. *Journal of Teacher Education*, *66*(2), 136–149. doi:10.1177/0022487114560646

Atkin, J. M., & Black, P. (2003). *Inside science education reform: A history of curricular and policy change*. New York, NY: Teachers College Press.

Bang, M., Medin, D., Washinawatok, K., & Chapman, S. (2010). Innovations in culturally based science education through partnerships and community. In M. S. Khine & M. I. Saleh (Eds.), *New science of learning: Cognition, computers, and collaboration in education* (pp. 569–592). New York, NY: Springer.

Barab, S. A., Thomas, M. K., Dodge, T., Squire, K., & Newell, M. (2004). Critical design ethnography: Designing for change. *Anthropology and Education Quarterly*, *35*(2), 254–268. doi:10.1525/aeq.2004.35.2.254

Bereiter, C. (2014). Principled practical knowledge: Not a bridge but a ladder. *Journal of the Learning Sciences*, *23*(1), 4–17. doi:10.1080/10508406.2013.812533

Biological Sciences Curriculum Study. (2006). *BSCS biology: A human approach* (3rd ed.). New York, NY: Kendall-Hunt.

Blumenfeld, P., Soloway, E., Marx, R. W., Guzdial, M., & Palincsar, A. S. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist*, *26*(3&4), 369–398. doi:10.1080/00461520.1991.9653139

Bryk, A. S., Gomez, L. M., Grunow, A., & LeMahieu, P. (2015). *Learning to improve: How America's schools can get better at getting better*. Cambridge, MA: Harvard University Press.

Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). *The BSCS 5E instructional model: Origins, effectiveness, and applications*. Colorado Springs, CO: Biological Sciences Curriculum Study.

Cobb, P. A., Jackson, K., Smith, T., Sorum, M., & Henrick, E. C. (2013). Design research with educational systems: Investigating and supporting improvements in the quality of mathematics teaching at scale. In B. J. Fishman, W. R. Penuel, A.-R. Allen, & B. H. Cheng (Eds.), *Design-based implementation research: Theories, methods, and exemplars* (pp. 320–349). New York, NY: Teachers College Record.

Coburn, C. E., Penuel, W. R., & Geil, K. (2013). *Research-practice partnerships at the district level: A new strategy for leveraging research for educational improvement*. Berkeley, CA, and Boulder, CO: University of California and University of Colorado.

Cole, M., & Engeström, Y. (2006). Cultural-historical approaches to designing for development. In J. Valsiner & A. Rosa (Eds.), *The Cambridge handbook on sociocultural psychology* (pp. 484–507). New York, NY: Cambridge University Press.

Danish, J. A. (2014). Applying an activity theory lens to designing instruction for learning about the structure, behavior, and function of a honeybee system. *Journal of the Learning Sciences*, *23*(2), 100–148. doi:10.1080/10508406.2013.856793

Ehn, P. (1992). Scandinavian design: On participation and skill. In P. S. Adler & T. A. Winograd (Eds.), *Usability: Turning technologies into tools* (pp. 96–132). New York, NY: Oxford University Press.

Engeström, Y. (1987). *Learning by expanding: An activity theoretical approach to developmental research*. Helsinki, Finland: Orienta-Konsultit.

Engeström, Y. (2007). Putting Vygotsky to work: The Change Laboratory as an application of double stimulation. In H. Daniels, M. Cole, & J. V. Wertsch (Eds.), *The Cambridge companion to Vygotsky* (pp. 363–382). New York, NY: Cambridge University Press.

Engeström, Y. (2009). From learning environments and implementation to activity systems and expansive learning. *Actio*, *2*, 17–33.

Engeström, Y. (2011). From design experiments to formative interventions. *Theory & Psychology*, *21*(5), 598–628. doi:10.1177/0959354311419252

Engeström, Y., & Sannino, A. (2010). Studies of expansive learning: Foundations, findings and future challenges. *Educational Research Review*, *5*, 1–24. doi:10.1016/j.edurev.2009.12.002

Engeström, Y., Sannino, A., & Virkkunen, J. (2014). On the methodological demands of formative interventions. *Mind, Culture, and Activity*, *21*(2), 118–128. doi:10.1080/10749039.2014.891868

Gutiérrez, K. D., & Jurow, A. S. (2016/this issue). Designing for new futures: The potential of social design experiments. *Journal of the Learning Sciences, 25*, XXX–XXX.

Gutiérrez, K. D., Rymes, B., & Larson, J. (1995). Script, counterscript, and underlife in the classroom: James Brown versus *Brown v. Board of Education*. *Harvard Educational Review*, *65*(3), 445–472. doi:10.17763/haer.65.3.r16146n25h4mh384

Ingersoll, R. M. (2003). *Who controls teachers' work? Power and accountability in America's schools*. Cambridge, MA: Harvard University Press.

Jurow, A. S., & Shea, M. (2015). Learning in equity-oriented scale-making projects. *Journal of the Learning Sciences*, *24*(2), 286–307. doi:10.1080/10508406.2015.1004677

Kensing, F., & Greenbaum, J. (2013). Heritage: Having a say. In J. Simonsen & T. Robertson (Eds.), *Routledge international handbook of participatory design* (pp. 21–36). London, UK: Routledge.

Konopasky, A. W., & Sheridan, K. M. (2016). Towards a diagnostic toolkit for the language of agency. *Mind, Culture, and Activity*, *23*(2), 108–123.

Krajcik, J. S., & Blumenfeld, P. C. (2006). Project-based learning. In R. K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 317–333). New York, NY: Cambridge University Press.

Krajcik, J. S., Codere, S., Dahsah, C., Bayer, R., & Mun, K. (2014). Planning instruction to meet the intent of the Next Generation Science Standards. *Journal of Science Teacher Education*, *25*(2), 157–175. doi:10.1007/s10972-014-9383-2

Kwon, S. M., Wardrip, P. S., & Gomez, L. M. (2014). Co-design of interdisciplinary projects as a mechanism for school capacity a growth. *Improving Schools*, *17*(1), 54–71. doi:10.1177/1365480213519517

Marx, R. W., Blumenfeld, P., Krajcik, J., & Soloway, E. (1997). Enacting project-based science. *Elementary School Journal*, *97*, 341–358. doi:10.1086/461870

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Research Council.

National Research Council. (2014). *Developing assessments for the Next Generation Science Standards*. Washington, DC: National Academies Press.

NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. Washington, DC: National Academies Press.

O'Neill, K. (2016/this issue). Understanding design partnerships in context and time: Why learning sciences scholars should learn from cultural-historical activity theory approaches to DBR. *Journal of the Learning Sciences, 25*.

Ormel, B. J. B., Roblin, N. N. P., McKenney, S. E., Voogt, J. M., & Pieters, J. M. (2012). Research-practice interactions as reported in recent design studies: Still promising, still hazy. *Educational Technology Research and Development*, *60*(6), 967–986. doi:10.1007/s11423-012-9261-6

Page, S. E. (2007). *The difference: How the power of diversity creates better groups, firms, schools, and societies*. Princeton, NJ: Princeton University Press.

Penuel, W. R. (2014). Emerging forms of formative intervention research in education. *Mind, Culture, and Activity*, *21*(2), 97–117.

Penuel, W. R., Roschelle, J., & Shechtman, N. (2007). Designing formative assessment software with teachers: An analysis of the co-design process. *Research and Practice in Technology Enhanced Learning*, *2*(1), 51–74. doi:10.1142/S1793206807000300

Penuel, W. R., Tatar, D., & Roschelle, J. (2004). The role of research on contexts of teaching practice in informing the design of handheld learning technologies. *Journal of Educational Computing Research*, *30*(4), 353–370. doi:10.2190/FJ51-5W3V-GGMC-4A92

Peters, V., & Slotta, J. (2009). Co-designing curricula to promote collaborative knowledge construction in secondary school science. In C. O'Malley, D. D. Suthers, P. Reimann, & A. Dimitracopoulou (Eds.), *Proceedings of the 9th international conference on computer supported collaborative learning* (Vol. 1, pp. 204–213). Rhodes, Greece: International Society of the Learning Sciences.

Polman, J. L. (2000). *Designing project-based science: Connecting learners through guided inquiry.* New York, NY: Teachers College Press.

Reiser, B. J. (2014, April). *Designing coherent storylines aligned with NGSS for the K-12 classroom*. Paper presented at the National Science Education Leadership Association meeting, Boston, MA.

Reiser, B. J. (2015, April). *Making sense of the world through science and engineering practices*. Paper presented at the National Science Teachers' Association national conference, Chicago, IL.

Reiser, B. J., Spillane, J. P., Steinmuler, F., Sorsa, D., Carney, K., & Kyza, E. (2000). Investigating the mutual adaptation process in teachers' design of technology-infused curricula. In B. Fishman & S. O'Connor-Divelbiss (Eds.), *Fourth international conference of the learning sciences* (pp. 342–349). Mahwah, NJ: Erlbaum.

Sandoval, W. A. (2014). Conjecture mapping: An approach to systematic educational design research. *Journal of the Learning Sciences*, *23*(1), 18–36. doi:10.1080/10508406.2013.778204

Sannino, A. (2010). Teachers' talk of experiencing: Conflict, resistance and agency. *Teaching and Teacher Education*, *26*, 838–844. doi:10.1016/j.tate.2009.10.021

Sannino, A., Engeström, Y., & Lemos, M. (2016/this issue). Formative interventions for expansive learning and transformative agency. *Journal of the Learning Sciences, 25*, XXX–XXX.

Severance, S., Leary, H., & Johnson, R. (2014). Tensions in a multi-tiered research-practice partnership. In J. L. Polman, E. Kyza, D. K. O'Neill, I. Tabak, A. S. Jurow, K. O'Connor, & W. R. Penuel (Eds.), *Proceedings of the 11th international conference of the learning sciences* (Vol. 2, pp. 1171–1175). Boulder, CO: International Society of the Learning Sciences.

Simonsen, J., & Robertson, T. (Eds.). (2013). *Routledge international handbook of participatory design*. London, UK: Routledge.

Snow, C. E. (2015). Rigor and realism: Doing educational science in the real world. *Educational Researcher*, *44*(9), 460–466. doi:10.3102/0013189X15619166

Spikol, D., Milrad, M., Maldonado, H., & Pea, R. (2009). Integrating co-design practices into the development of mobile science collaboratories. In I. Aedo, N.-S. Chen, K. D. G. Sampson, & L. Zaitseva (Eds.), *Proceedings of the Ninth IEEE International Conference on Advanced Learning Technologies* (pp. 393–397). Riga, Latvia: IEEE.

Taylor, K. H., & Hall, R. (2013). Counter-mapping the neighborhood on bicycles: Mobilizing youth to reimagine the city. *Technology, Knowledge, and Learning*, *18*(1–2), 65–93. doi:10.1007/s10758-013-9201-5

Tyack, D., & Cuban, L. (1995). *Tinkering toward utopia: A century of public school reform*. Cambridge, MA: Harvard University Press.

Valsiner, J., & van der Veer, R. (2000). *The social mind: Construction of the idea*. New York, NY: Cambridge University Press.

van der Veer, R. (2008). Multiple readings of Vygotsky. In B. van Oers, W. Wardekker, E. Elbers, & R. van der Veer (Eds.), *The transformation of learning: Advances in cultural-historical activity theory* (pp. 20–37). New York, NY: Cambridge University Press.

Virkkunen, J. (2006). Dilemmas in building shared transformative agency. *Activités*, *3*(1), 43–66.

Voogt, J. M., Laferrière, T., Breuleux, A., Itow, R. C., Hickey, D. T., & McKenney, S. E. (2015). Collaborative design as a form of professional development. *Instructional Science*, *43*(2), 259–282. doi:10.1007/s11251-014-9340-7

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press. (Original work published 1934)

Vygotsky, L. S. (1987). *Thought and language* (A. Kozulin, Trans.). Cambridge, UK: Cambridge University Press.