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Conjecture Mapping: An Approach to Systematic Educational Design Research

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Design research is strongly associated with the learning sciences community, and in the 2 decades since its conception it has become broadly accepted. Yet within and without the learning sciences there remains confusion about how to do design research, with most scholarship on the approach describing what it is rather than how to do it. This article describes a technique for mapping conjectures through a learning environment design, distinguishing conjectures about how the design should function from theoretical conjectures that explain how that function produces intended outcomes.

Since being formally named two decades ago (A. L. Brown, 1992; Collins, 1992), design research has evolved into an accepted paradigm of educational research. A handbook has been devoted to it (Kelly, Lesh, & Baek, 2008), its putative contribution to educational research has been located (Levin & O'Donnell, 1999; National Research Council, 2002), and special issues of well-regarded and influential journals (Barab, 2004; Kelly, 2003; Sandoval & Bell, 2004) and edited volumes (Dai, 2012; Van den Akker, Gravemeijer, McKenney, & Nieveen, 2006) have been devoted to its characterization. The legitimacy of design research is evident in its inclusion in various handbooks of education research (Sandoval, in press; Schoenfeld, 2006), including two different chapters in the first handbook on the learning sciences (Barab, 2006; Confrey, 2006).

Despite this boom in writing and move into the mainstream, there remains confusion about design research as a methodology. Most recent characterizations of design research suggest that it is an approach with certain commitments: the

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production of innovative learning environments, knowledge about how such environments work in the settings for which they are designed, and, hopefully, some more fundamental knowledge about learning or teaching (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Design-Based Research Collective, 2003; Edelson, 2002). Various approaches to education research hold one or another of these commitments, but it is argued that the unique attribute of design research is the simultaneous concern for all of them. Yet this commitment to certain kinds of research outcomes without a clear description of research methods has produced considerable criticism against design research. One set of critiques centers on assertions that design research lacks methodological rigor or clear standards (Dede, 2004; Kelly, 2004; Shavelson, Phillips, Towne, & Feuer, 2003). Another critique is that design research fundamentally cannot live up to the claim of *simultaneous* design evaluation and theory building (Phillips & Dolle, 2006).

Responding to such criticisms demands moving beyond reflections about the kinds of knowledge design research can produce to develop systematic approaches to the conduct of design research. There are surely a number of researchers within the learning sciences community who are conducting systematic design research, but we are not talking much about how we do it or how not to do it. The burst of articles and books that have appeared within the past decade have largely articulated an ethos of design research, described in terms of aims or commitments of the approach, sometimes including exemplars of research programs that reify those commitments. Research models, when proposed, are described at a very high level (Bannan-Ritland, 2003; Edelson, 2002; Gravemeijer & Cobb, 2006; Middleton, Gorard, Taylor, & Bannan-Ritland, 2008).

Here I describe a technique for conceptualizing design research that I call *conjecture mapping,* a means of specifying theoretically salient features of a learning environment design and mapping out how they are predicted to work together to produce desired outcomes. Mapping the conjectures guiding a design can guide the systematic test of particular conjectures about learning and instruction in specific contexts. To be clear, my interest here is not in how to design learning environments per se but rather is to articulate a way of conceptualizing and carrying out research on learning environments.

I hope to show that conjecture mapping addresses two methodological concerns. The first is Kelly's (2004) critique that design research lacks an argumentative grammar. An argumentative grammar is "the logic that guides the use of a method and that supports reasoning about its data" (Kelly, 2004, p. 118). For Kelly, an argumentative grammar is what provides the *logos* for a methodology. It may be that design research is not a methodology in this sense, as there is no clearly identifiable set of methods that can be labeled as design research. Design research is defined mainly in terms of certain epistemic commitments that include, among others, the joint pursuit of practical improvement and theoretical refinement; cycles of design, enactment, analysis, and revision; and attempts to link processes of enactment to outcomes of interest. These require concomitant methodological commitments to methods that can link elements of designed learning environments to the processes through which those designs are enacted in particular settings and link such observed processes to observed outcomes of any intervention. Yet design researchers have shown that such commitments can be met through an array of research methods.

The second concern is the assertion by Phillips and Dolle (2006) that design research cannot actually meet one of its basic commitments: the simultaneous evaluation of designs and testing of theory. I see this focus on simultaneity as stemming from a misunderstanding of how design research is actually carried out, but it is a misunderstanding largely promulgated by how design research proponents describe what we are doing. I propose conjecture mapping as a method for articulating the joint design and theoretical ideas embodied in a learning environment in a way that supports choices about the means for testing them. Thus, conjecture maps clarify how a research team views the concurrent effort of practical improvement and theoretical refinement in terms that include at least some elements of an argumentative grammar.

In what follows, I describe what I mean by a conjecture map in general terms and outline how it provides at least some features of an argumentative grammar for design research. I then sketch an example of building and refining a conjecture map to illustrate how such maps can be used to organize empirical research. I conclude by returning to the issue of argumentative grammar and how conjecture mapping can support empirically grounded claims about the causal mechanisms of effective learning environments.

MAPPING AND TESTING CONJECTURES THROUGH EDUCATIONAL DESIGNS

The basic tension in educational design research is the dual commitment to improving educational practices and furthering our understanding of learning processes. This dual interest in fundamental understanding and usable application is characteristic of a variety of scientific work (Stokes, 1997). The approach I describe here starts from the assumption that the design of learning environments is a theoretical activity, that learning environments intrinsically embody hypotheses about how learning happens in some context and how to support it (Cobb et al., 2003; Sandoval, 2004). This means that even in the most exploratory efforts to design some intervention, design work is informed by ideas of how learning might happen or be made to happen. Consequently, as researchers (and not just designers) we have an obligation to be as explicit as possible, *in advance,* about what those ideas are. Conjecture mapping is an effort to reify specific conjectures and how they are expected to function in interaction to promote learning. Such specification leads to empirical predictions that can be tested, and the results of such tests can lead to both refinements of a particular design as well as refinements of a theoretical perspective (Sandoval, 2004).

Cobb and colleagues have been most explicit in describing their work as a methodological approach, identifying phases of their approach to design research and the work they do in each phase (Gravemeijer & Cobb, 2006). Their reflection on their approach to design research is quite helpful in articulating the role that theory has to play in instructional design and describing how classroom experimentation (in the broad sense of that word) can lead to theoretical refinement. Yet their writing inscribes their approach in very general terms—the components of a design are not enumerated in their representations of research cycles, nor are the specific conjectures or their relations to designed elements. This is true of other models of design research that focus on articulating a model of research that obscures the features of designs and the role of design in the research (Bannan-Ritland, 2003; Barab, 2006; Collins, Joseph, & Bielaczyc, 2004). Conjecture mapping is an attempt to provide a means for specifying such design relationships, to make them concrete. A conjecture map reflects a research team's commitment to what it sees as the most important design problem to be solved and its initial ideas of the important questions to ask and the "varying degrees of uncertainty" (Walker, 2006, p. 11) about those questions.

Elements of a Conjecture Map

Figure 1 shows a generalized form of a conjecture map; read from left to right. The map contains six major elements and their relationships. Whatever the context, learning environment designs begin with some *high-level conjecture(s)* about how to support the kind of learning we are interested in supporting in that context. That conjecture becomes reified within an *embodiment* of a specific design. That embodiment is expected to generate certain *mediating processes* that produce

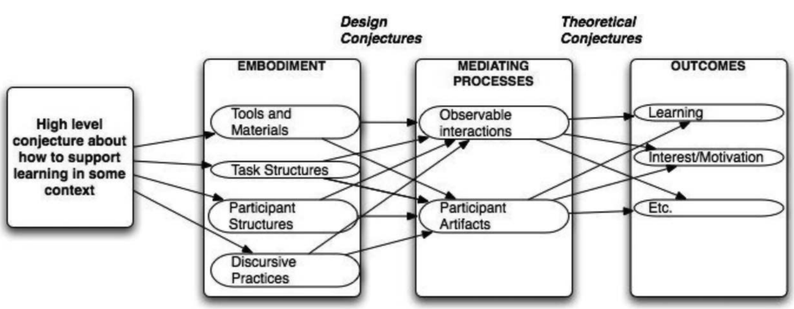

FIGURE 1 Generalized conjecture map for educational design research.

desired *outcomes.* The ideas a research team has about how embodied elements of the design generate mediating processes can be articulated as *design conjectures.* The ideas a team has about how those mediating processes produce desired outcomes are *theoretical conjectures.* Each element and their relations are explicated here.

I use the term *conjecture* here to connote the usually highly provisional nature of the ideas we have about how to design a learning environment at the start of a design research project. Design research typically aims to create novel conditions for learning that theory suggests might be productive but are not common or well understood (Design-Based Research Collective, 2003). By *high-level conjecture,* I mean this sort of theoretically principled idea of how to support some desired form of learning, articulated in general terms and at too high a level to determine design. Such conjectures or meta-principles (Kali, 2006) are usually the result of some initial problem analysis (cf. Edelson, 2002). The aim of mapping a high-level conjecture through a particular design is to get specific about how it is expected to operate within a particular context. How does it drive the design of the learning environment? How are theoretically salient design elements expected to function in the intended setting? How do those functions lead to the desired outcomes? A conjecture map helps to hypothesize answers to these questions and thereby suggests means for testing them.

The *embodiment* of the high-level conjecture articulates its reification in features of the learning environment design. Conjectures can be embodied within four kinds of elements of learning environments: tools and materials, task structures, participant structures, and discursive practices. The most obvious element includes the tools and materials that are designed. These tools include software programs, instruments, manipulable materials, media, and other resources. Tools are the things we usually have in mind when we think about design, harkening back to the original formulation of design experiments as evaluating learning technologies (Collins, 1992).

It is now well established that learning environment designs have to concern themselves with changing the social infrastructure of the settings in which they function (Bielaczyc, 2006). Two critical aspects of tool use to specify therefore include task structure and participant structure (Erickson, 1982). *Task structure* refers to the structure of the tasks learners are expected to do—their goals, criteria, standards, and so on. *Participant structure* refers to how participants (e.g., students and teachers) are expected to participate in tasks, the roles and responsibilities participants take on. A final element of design includes intended discursive practices—ways of talking, in the simplest sense. This element reflects the claim that desirable discursive modes can be at least partially designed. These four elements of learning environments embody conjectures about learning in multiple, interacting ways. That is, tools, task and participant structures, and discursive practices are all intended to work together to achieve a design. Naturally, any particular learning environment design may not include all of these four elements. The reciprocal teaching effort described in A. L. Brown's (1992) seminal paper focused on redesigning task and participant structures without novel technologies, for example.

A final point about the embodied elements of designs is that they are typically socially and temporally distributed. Students in a classroom, for example, participate in different tasks at different times, and the material or social scaffolds designed to support such participation therefore, obviously, change over time too. We expect that scaffolds embodied in a design can be faded over time as learners appropriate new modes of participation or discourse. Mapping such distributions in a design and how they are expected to interact and function with other designed elements is critical to clarifying researchers' understanding of the "crucial components and relations" (Engeström, 2008, p. 4) of a design.

Not every feature of a learning environment is theoretically salient. The salient features are those expected to lead to *mediating processes.* Designs do not lead directly to outcomes. An airplane produces flight as an outcome to the extent that it generates sufficient lift, a mediating process required to produce the outcome. In learning environments, the use of particular tools for specific tasks enacted in specific ways is intended to produce certain kinds of activity and interaction that are hypothesized to produce intended outcomes. These hypothesized interactions mediate the production of those outcomes. We could refer to these as meditational means from within a Vygotskian (Vygotsky, 1978) perspective, or we could think of them as the functions enabled by the structures of a design from an engineering perspective (cf., Middleton et al., 2008). I label them *processes* to emphasize the process–outcome link of concern to design research.

Figure 1 does not show possible mediating processes. Rather, it shows two ways of understanding the mediating processes that emerge from a design. The first way includes observable interactions between participants and the designed environment. Observable interactions can directly show how embodied elements of a design mediate participants' interaction, and thus learning. The second way to understand mediating processes is to analyze artifacts that participants produce from their activity. Such artifacts are proxies for learning processes; they indicate the extent to which learners are engaged in the sort of activity and thinking hypothesized to matter. I would argue that documenting mediating processes in at least one of these two ways is required to connect aspects of a designed learning environment to observed outcomes of its use.

Mediating processes are intended to produce desired *outcomes.* Different design research projects could pursue a wide variety of outcomes and could take a wide variety of approaches to gathering evidence of those outcomes. The outcomes element in Figure 1 is deliberately vague to accommodate such variety, but the success of any design endeavor requires making some commitment to articulating what desired outcomes will look like and how they might be observed or measured. This is true even if researchers' ideas about what the desired outcomes should be change as a result of study (cf. O'Neill, 2012). Conjecture maps for particular designs should be as specific as possible about what the desired outcomes are.

These three elements—embodiments, mediating processes, and outcomes—provide the structure for mapping specific, testable conjectures of the relations among them. Design research fundamentally concerns two types of conjectures related to the two conjoint commitments to educational change and theoretical development. *Design conjectures* take the general form "if learners engage in this activity (task + participant) structure with these tools, through this discursive practice, then this mediating process will emerge." Testing such a conjecture requires methods that can identify whether the expected mediating process does in fact emerge and that can provide evidence to trace that process back to designed elements. The common reliance on video data in design research is a response to this demand (Derry et al., 2010), as are the analytic approaches developed to understand interactions (Jordan & Henderson, 1995). Recall that interactions are only one means of observing mediating processes. Artifacts created through learning activities can serve as proxies for mediating processes. Analyses of such artifacts can uncover how participants interpret designed activity structures and tools and can help to explain their performance. Clearly, whether the capture and analysis of interactions or artifacts is required in any given research effort depends upon the designed environment and the research aims (and could also change over time within a particular project).

Theoretical conjectures in a conjecture map take the general form "if this mediating process occurs it will lead to this outcome." As with design conjectures, there is an aspect of testing such a conjecture that appears to require analysis of interaction in order to trace back from outcome to process, but theoretical conjectures also require appropriate measurement of targeted outcomes. This obviously demands appropriate instrumentation, and it may well be the case that instrumentation is a neglected aspect of design research (Schwartz, Chang, & Martin, 2008). Two features common to design research emphasize measurement as a critical issue. First, design research often aims to innovate not just processes of instruction but the kinds of outcomes desired from instruction. Consequently, commonly available tests are inappropriate measures of ambitious outcomes. Second, it can be the case that the nature of desired outcomes is not very well conceived at the start of a design research project, and early cycles of design research may be needed to clarify how those outcomes might be measured (Schwartz et al., 2008, hold the opposite view, that design research can productively start from considerations of assessment).

Together the elements of a conjecture map capture the hypothesized learning trajectory (Cobb et al., 2003) embodied within a designed learning environment. It is crucial to understand that such trajectories are hypothesized not in abstract notions of learners' capabilities (such as developmental level or reasoning ability) but explicitly in relation to given means of support. Engeström (2008) recently argued that writing about design research tends to be vague about representations of design, and that a failure to model the crucial components and relationships in a designed innovation severs needed links between theory and method. Conjecture maps render explicit researchers' hypotheses about those crucial components and their relationships. I see this as a core value of the mapping process, although other recent models of design research may achieve this (e.g., Middleton et al., 2008). Another major value of conjecture maps, in my view, is that they can be used to distinguish design conjectures from theoretical conjectures, a distinction that seems rarely, if ever, made explicit in writing about design research. To be clear, this is a distinction between conjectures about how a design functions and conjectures about how those functions produce learning.

Developing Conjecture Maps

It could be argued that the space of potentially important relationships to specify for any given learning environment could easily swamp any map-like representation. I view the advantage of conjecture maps as being a means to specify the most salient relationships in a design. That is, developing a conjecture map forces a commitment to the operating conjectures, however nascent, guiding a design. An example will help to illustrate this advantage.

This example comes from a recent effort to promote scientific argumentation in elementary science. The high-level conjecture our research team started with was that argumentation is a discursive practice more than a particular kind of task. Yet initially we conceived of this discursive practice as emerging out of specific kinds of task and participant structures. The initial set of conjectures is mapped in Figure 2. The high-level conjecture guiding our work, like most such ideas in design research, was derived from our analysis of the problem, including relevant

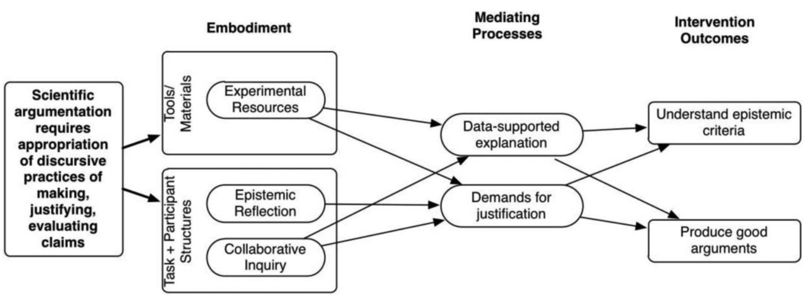

FIGURE 2 Initial conjecture map of a design to promote argumentation in elementary science.

research and our own prior work. As suggested in Figure 2, the design was primarily focused on changing the joint task and participant structures in the classroom.

My aim here is to exemplify conjecture mapping rather than justify or explain this particular research, so I highlight only some features of the map to illustrate its utility for guiding research. First, this is an example in which tool and material development was not primary. The only material resources we considered part of the design were FOSS kits teachers were already using in their classrooms, the “experimental resources” listed in Figure 2. (The “we” here included a core team of two university professors, a doctoral student, and three collaborating teachers, plus other graduate students and teachers at various points of the project.) Our design work involved reconfiguring how children worked with these materials rather than the materials themselves. This centered on two core features. The first feature was a sequence of lessons we designed for the start of the year that focused on “epistemic reflection” and specifically on getting children to think about how they know what they know. The second feature was that we organized inquiry collaboratively, with the expectation that working together would induce children to argue about how to do things and how to interpret results. This collaborative inquiry also included framing particular investigations in ways that children had responsibility for defining problems, designing experiments, representing data, and communicating findings to each other. We expected that these activities would lead to the epistemic interactions listed in Figure 2 as mediating processes, which would then produce the desired outcomes listed.

The second thing to notice is that we hypothesized only two kinds of interactions as the most important mediating processes to engineer. That is, the goal is not to think of every possible sort of interaction that might occur and fit it into some model but to express a commitment to the meditational means most likely to produce desired outcomes. Naturally, such hypotheses might be wrong, but it is precisely the aim of empirical work to test them.

The third thing to notice about the map is that it identifies embodied elements and the mediating processes they are hypothesized to induce, but it does not express how embodied elements work together. The actual design conjectures are more accurately expressed as propositions, for example, “collaborative inquiry with experimental resources will lead to data-supported explanation and demands for justification” and “epistemic reflection will promote demands for justification.” These conjectures focus empirical observation; they are things to be looked for in actual enactments. The final thing to notice about the map is that it claims that the hypothesized mediating processes jointly produce all desired outcomes. This reflects a notion similar to Salomon’s (1996) argument that studying learning environments involves finding “patterns of change.” His idea was that the complexity of naturalistic learning environments implies that they cannot realistically be decomposed into particular parts that have particular effects. Instead, in specific settings specific designs lead to new patterns of change.

How Conjecture Maps Can Organize Research

Conjecture maps are intended to organize design research by focusing researchers' attention on the aspects of a designed learning environment considered theoretically salient. One way this benefit can be seen is simply in the effort to construct a conjecture map. Doing this requires a research team to be specific not just about what it is trying to design but also about what particular features of the design are expected to do, how they are expected to work together, and what they ought to produce. Each arrow in a conjecture map specifies a relation open to empirical refinement.

To return to the example of Figure 2, at the start we did not have clear ideas of how to assess epistemic understanding or argument competence independently of children's understanding of particular science topics they had studied. Moreover, the highest degree of uncertainty for us was whether, in fact, epistemic reflection and collaborative inquiry would shift the discourse in the classroom. Consequently, our initial empirical work focused on documenting conjectured mediating processes. Our interaction analyses of the classrooms of two different teachers showed how they differentially framed those task and participant structures in relation to an overarching classroom discourse. Where the discourse was focused on building consensus, more productive arguments occurred. This led us to recognize the importance of trying to design discursive practice, as indicated in Figure 3.

Figure 2 and Figure 3 together show how conjecture maps can reflect the trajectory of conjectures over the course of a design research project. It is worth noting that the emergence of discursive practice as an important element to design

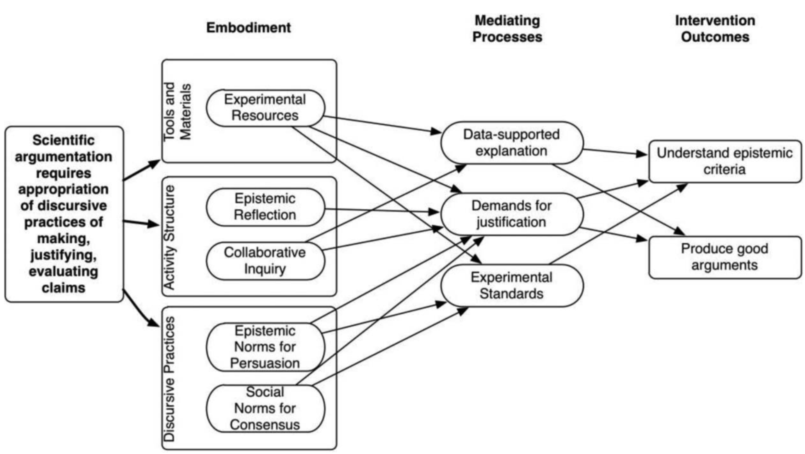

FIGURE 3 Revised conjecture map for supporting argumentation in elementary science.

was due to the differential emergence of desired mediating processes in different classrooms. Interaction analysis highlighted the role of one teacher's focus on developing norms for persuasion and consensus in creating and sustaining those processes. We also saw a new kind of interaction that seemed important—that children commonly argued about experimental standards, and that such arguments seemed central to their developing ideas about sound argumentation. Over the same course of time, about 1 year, as we saw children's competence in interaction we were able to develop measures of our outcomes of interest. A detailed report of how changes in those outcomes can be traced to children's appropriation of the epistemic and social norms referenced in Figure 3 can be found in Ryu and Sandoval (2012).

There are many details lacking from this example, of course. I only intend to illustrate how the effort to map particular conjectures about how to support learning through their embodiment, mediating processes, and consequent outcomes can guide design research productively. Our uncertainty about our design conjectures demanded that they be the focus of initial work, and this illuminated both the functions and limits of those designed elements while revealing the crucial role of discursive practices in a way we had not fully conceptualized at the start. These emergent empirical findings were then fed back into the design and a revised model of its function (see Figure 3). Then, once intended mediating processes were at least partially observed we could consider issues of outcome measurement. This allowed for a preliminary assessment of the high-level theoretical conjecture: that individual children could appropriate discursive practices and display independent competence at argument. The focus on design versus theoretical conjectures in other design research projects would be expected to vary from this example according to the degree of certainty of the various conjectures at play, as would the focus on interaction analysis versus outcome measurement.

CONJECTURE MAPS AS AN ARGUMENTATIVE GRAMMAR FOR DESIGN RESEARCH

As a means of inscribing the set of relationships proposed to matter in supporting learning in a particular context, conjecture maps seem to satisfy some of Kelly's (2004) requirements for an argumentative grammar. A conjecture map distinguishes conjectures about how designed features of a learning environment will function in their intended setting from conjectures about how such functions mediate learning and produce intended outcomes. These distinctions lead to methodological demands one could make of particular design research studies or reports: Have hypothesized mediating processes been specified? Have these been linked to particular interactions among designed elements? Have methods for tracing these links been articulated and justified? Have links between mediating processes and outcomes been articulated and justified? Have methods been presented to link outcome measurements to observed mediating processes?

Such questions ask for causal attribution and justification. The central question animating educational design research is not simply whether something works but how a learning environment works (Design-Based Research Collective, 2003). An argumentative grammar for design research should include a logic for making causal attributions about design functions. More than this, such a grammar should be able to address the critique that simultaneous design evaluation and theory development is not possible (Phillips & Dolle, 2006).

I claim that conjecture maps can provide, at least partially, such an argumentative logic. We should, however, keep in mind two caveats. First, satisfying the syntactic requirements of a particular argumentative grammar, such as the randomized field trials touted by Kelly (2004), does not guarantee either rigor or quality. Second, science studies suggest that argumentative grammars develop *through* particular research efforts, not apart from them (e.g., Feyerabend, 1975/1993; Pickering, 1995). Both points suggest that quality and rigor are ultimately found in particular descriptions of research rather than abstract grammars. Nevertheless, it is worth explicating the "epistemic threads" (Engeström, 2008) that run through this view of design research and that can be made visible to varying degrees through conjecture maps. These threads concern causal attribution in design research, the inherently contextual nature of design research, and conceptualizations of trajectories of studies in design research. The technique of conjecture mapping articulated so far addresses causal attribution directly but is limited with respect to concerns about context and trajectory.

Causal Process

A great deal of the discussion of educational research is concerned with the demonstration of causal effects. My view of design research is that its primary focus is on explicating causal processes. This is a view of causality that Maxwell (2004) identified with an epistemology of scientific realism as opposed to the traditional view of causal regularity identified with David Hume centuries ago. The regularity view presupposes that causal processes cannot be seen but only inferred through the regular co-occurrence of two events, A and B, such that A can be inferred to cause B. The scientific realism view described by Maxwell presumes that causal processes can be observed. This notion of causality is fundamentally multivariate and multirelational and explains Cronbach's (1975) identification of the limitations of variable-oriented approaches to the study of interventions. Bereiter (2002) made the point that analyzing variables and their interactions does not help designers very much, partially for Cronbach's reasons—there are too many variables and way too many interactions. More fundamentally, the elements that make up a design are not easily captured as variables: "Collaborative inquiry," to use the previous example, is not a variable but a complex form of activity. Designs can be, and need to be, decomposed; their components need to be analyzed and their functions—in interaction—understood. Yet this is a fundamentally different process than testing for effects. As Bereiter said, the classical researcher tears the design apart into finer and finer grained details in the process moving further and further away from the design itself.

Conjecture maps, therefore, should not be read as a set of factors leading to effects but as the specification of process relations, as a pattern of change (Salomon, 1996). Design research, as a means of uncovering causal processes, is oriented not to finding effects but to finding *functions,* to understanding how desired (and undesired) effects arise through interactions in a designed environment. Such functions themselves arise from complex interactions between multiple elements of a design and the people who encounter them in a particular setting. This demands methods that allow for the observation and analysis of such interactions. The function of the social and epistemic norms in Figure 3 is to support particular mediating processes, like demands for justification, but those norms function only in relation to the other elements in the learning environment, not as an isolated variable. Close observations of classroom talk across whole-class and students' small-group work showed how the teacher both introduced norms herself and solicited norms from students and how students subsequently took up previously established norms in their spontaneous work (Ryu & Sandoval, 2012).

The elements of a conjecture map provide a syntax for articulating hypothesized interactions between designed elements and the people who act within a designed environment. As a grammar, then, we can ask of any particular study whether the pieces of this syntax have been articulated (as Kelly, 2004, for example, described how any randomized trial must adhere to the syntactic requirement of random assignment). Evaluations of any particular design research study can scrutinize specifically proposed interactions and the subset of design and/or theoretical conjectures being tested. In this way, conjecture maps potentially provide a means for assessing rigor and quality, by linking study methods to the conjectures specified in a map.

Context

Design research assumes that learning is contextual, and thus designs for learning are contextualized. This assumption carries basic implications for the causal claims one can make from design research. A critical point not yet addressed is the challenge raised by Tabak (2004): The boundaries of any designed learning environment as it is enacted are blurry, as the exogenous elements created by the designer and imported into a particular setting mingle with endogenous elements of practice already at work in that setting. More than this, design research projects vary considerably in terms of what is designed in advance and what coevolves during multiple cycles of enactment with collaborators (e.g., Gravemeijer & Cobb, 2006; Zhang, 2012). Conjecture maps as articulated here do not clearly help with this problem, as the maps are primarily intended to help design researchers explicate the elements of exogenous design hypothesized to matter within a given context. At the same time, as I have suggested here and argued before (Sandoval, 2004), the effort to observe specific mediating processes requires distinguishing them from other forms of interaction, and this appears quite often in design research to lead to the observation of unexpected endogenous or emergent mediating processes of both theoretical and practical value (diSessa & Cobb, 2004).

Context matters centrally to design research precisely because the orientation to causal process locates such processes in specific settings. As Cronbach said 40 years ago:

> An observer collecting data in one particular situation is in a position to appraise a practice or proposition in that setting, observing effects in context. In trying to describe and account for what happened, he will give attention to whatever variables were controlled, but he will give equally careful attention to uncontrolled conditions, to personal characteristics, and to events that occurred during treatment and measurement. As he goes from situation to situation, his first task is to describe and interpret the effect anew in each locale, perhaps taking into account factors unique to that locale of series of events (cf. Geertz, 1973, chap. 1, on "thick description"). As results accumulate, a person who seeks understanding will do his best to trace how the uncontrolled factors could have caused local departures from the modal effect. That is, generalization comes late, and the exception is taken as seriously as the rule. (Cronbach, 1975, pp. 124–125)

Thus, we can frame the task of design research as recreating and interpreting outcomes across multiple settings and tracing how both designed and nondesigned factors contribute to those outcomes. Describing causal processes thus requires this attention to contextual variation, both within any single design study and across them.

The current formulation of conjecture maps has to be expanded to explicitly represent contextual variations. One could obviously create different maps for different contexts. More realistically, it seems likely that the relations between design elements and mediating processes are affected by contextual variations, and work across multiple contexts could perhaps illuminate key variations and their influences. Over time, such influences would most likely be fed back into the design itself, as in the previous example in which comparisons between teachers led to the revisions depicted between Figure 2 and Figure 3. A similar line of reasoning could be followed for theoretical conjectures, and work across multiple contexts could uncover varieties of mediating processes that converge to similar outcomes.

Trajectory

Writing about design research can promulgate a notion of innovation as linear, moving straightforwardly from small- to large-scale implementation (e.g., Bannan-Ritland, 2003; Confrey, 2006; Edelson, 2002; Middleton et al., 2008). It is not at all clear, however, that a trajectory from smaller to larger scale is the only or best trajectory for design research. Taking the context issue seriously, in fact, suggests research trajectories as pursuing contextual variation. The use of larger studies, in terms of more sites, is only one way to get such variation and comes at the cost of limiting a research team's capacity to make close observations of each variation. An alternative view of trajectory is to see the aim as moving to new contexts at the same scale, where new contexts are chosen to illuminate the influence of Cronbach's (1975) "local departures" and generate clearer accounts of the elements of a design that seem most important to producing desired outcomes (and perhaps limiting undesired ones).

It may be, of course, that a trajectory of design research in terms of increasing scale makes sense. Some design research aims to develop products that can be exported beyond the contexts in which they are developed and studied, such as Jasper (Cognition and Technology Group at Vanderbilt, 1992) or ThinkerTools (White, 1993) and many other possible examples. Other design research efforts focus more on developing and sustaining communities organized around their own improvement. Examples of this latter sort of design research include CSILE/KnowledgeForum (Bereiter & Scardamalia, 2006; Scardamalia & Bereiter, 1993) and Fifth Dimension (K. Brown & Cole, 2002; Scott, Cole, & Engel, 1992). Product-oriented variants of design research have more finality to them than improvement-oriented variants. Both variants, however, share a focus on the development of explanatory concepts that can be exported or generalized.

The development of generalizable explanations of design functions requires a trajectory of studies, and design research is more productively seen as such a trajectory rather than a particular kind of study or experiment (Confrey, 2006; Design-Based Research Collective, 2003). Viewing design research as a trajectory sidesteps the complaint that a design experiment cannot simultaneously evaluate an intervention and test a theory (Phillips & Dolle, 2006). Particular design studies can focus on design conjectures and others on theoretical conjectures. That said, it remains the case that design research reports too often omit needed details of how the data analyzed from one enactment lead to, and justify, design revisions (Ormel, Roblin, McKenney, Voogt, & Pieters, 2012). Ormel and colleagues (2012) suggested that publication biases may need to change to support such reports.

The current formulation of conjecture maps does not easily capture movement along a research trajectory, but there are a couple of ways they might be used to envision one. With any particular map, a sequence of studies might be designed to explore varying subsets of conjectures. This might be especially helpful at the start of a design research effort, when design conjectures are quite tentative and need to be pilot-tested. A longer trajectory might be represented as a sequence of conjecture maps, as in my example here, in which particular design or theoretical relationships are deleted, modified, or added. The advantage of the map is that it specifies the conjectured relations that should be the focus of empirical attention within and across particular studies.

CONCLUSIONS

My aim here has been to describe a technique for specifying design research commitments explicitly and concretely as a means of supporting systematic design research and addressing concerns about the methods of design research. Mapping design and theoretical conjectures through a novel learning environment design focuses attention on the elements of the design and their predicted functions that most require study. The process is particularly helpful in rendering explicit researchers' commitment to what they see as the most salient design and theoretical conjectures and assisting in the attribution of failure to either the design or the underlying theoretical rationales. It is only one out of many possible ways of describing and conducting educational design research, given the theoretical breadth animating design research (Bell, 2004), and there are certainly limitations to its current formulation. One hope is that the example will encourage others to articulate alternative models. The value of conjecture mapping lies in it being a more specific articulation of the how of design research than has so far been common in the learning sciences literature. By promoting the specification of the complex series of relations between features of a design, the mediating processes that design should enable, and the outcomes thus derived, conjecture mapping can promote more systematic design research programs that produce not only sound instructional designs but trustworthy, usable theories of learning.

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REFERENCES

Bannan-Ritland, B. (2003). The role of design in research: The integrative learning design framework. *Educational Researcher*, *32*(1), 21–24.
Barab, S. A. (Ed.). (2004). Design-based research: Clarifying the terms [Special issue]. *Journal of the Learning Sciences*, *13*(1).
Barab, S. A. (2006). Design-based research: A methodological toolkit for the learning sciences. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 153–172). New York, NY: Cambridge University Press.
Bell, P. (2004). On the theoretical breadth of design-based research in education. *Educational Psychologist*, *39*(4), 243–253.
Bereiter, C. (2002). Design research for sustained innovation. *Cognitive Studies, Bulletin of the Japanese Cognitive Science Society*, *9*(3), 321–327.
Bereiter, C., & Scardamalia, M. (2006). Education for the knowledge age: Design-centered models of teaching and instruction. In P. A. Alexander & P. H. Winne (Eds.), *Handbook of educational psychology* (2nd ed., pp. 695–713). Mahwah, NJ: Erlbaum.
Bielaczyc, K. (2006). Designing social infrastructure: Critical issues in creating learning environments with technology. *Journal of the Learning Sciences*, *15*, 301–329.
Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *Journal of the Learning Sciences*, *2*, 141–178.
Brown, K., & Cole, M. (2002). Cultural historical activity theory and the expansion of opportunities for learning after school. In G. Wells & G. Claxton (Eds.), *Learning for life in the 21st century: Sociocultural perspectives on the future of education* (pp. 225–238). Oxford, England: Blackwell.
Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, *32*(1), 9–13.
Cognition and Technology Group at Vanderbilt. (1992). The Jasper series as an example of anchored instruction: Theory, program description, and assessment data. *Educational Psychologist*, *27*(3), 291–315.
Collins, A. (1992). Toward a design science of education. In E. Scanlon & T. O'Shea (Eds.), *New directions in educational technology* (pp. 15–22). New York, NY: Springer-Verlag.
Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *Journal of the Learning Sciences*, *13*, 15–42.
Confrey, J. (2006). The evolution of design studies as methodology. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 135–151). New York, NY: Cambridge University Press.
Cronbach, L. J. (1975). Beyond the two disciplines of scientific psychology. *American Psychologist*, *30*(2), 116–127.
Dai, D. Y. (Ed.). (2012). *Design research on learning and thinking in educational settings*. London, England: Routledge.
Dede, C. (2004). If design-based research is the answer, what is the question? *Journal of the Learning Sciences*, *13*, 105–114.
Derry, S. J., Pea, R. D., Barron, B., Engle, R. A., Erickson, F., Goldman, R., . . . Sherin, B. L. (2010). Conducting video research in the learning sciences: Guidance on selection, analysis, technology, and ethics. *Journal of the Learning Sciences*, *19*, 3–53.
Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, *32*(1), 5–8.
diSessa, A. A., & Cobb, P. (2004). Ontological innovation and the role of theory in design experiments. *Journal of the Learning Sciences*, *13*, 77–103.
Edelson, D. C. (2002). Design research: What we learn when we engage in design. *Journal of the Learning Sciences*, *11*, 105–121.

Engeström, Y. (2008). From design experiments to formative interventions. In P. Kirschner, F. Prins, V. Jonker, & G. Kanselaar (Eds.), *International perspectives in the learning sciences: Cre8ing a learning world. Proceedings of the Eighth International Conference for the Learning Sciences—ICLS 2008* (pp. 3–24). Utrecht, The Netherlands: International Society of Learning Sciences.

Erickson, F. (1982). Classroom discourse as improvisation: Relationships between academic task structure and social participation structures in lessons. In L. C. Wilkinson (Ed.), *Communicating in the classroom* (pp. 153–181). New York, NY: Academic Press.

Feyerabend, P. (1993). *Against method* (3rd ed.). New York, NY: Verso. (Original work published 1975).

Gravemeijer, K., & Cobb, P. (2006). Design research from a learning design perspective. In J. Van den Akker, K. Gravemeijer, S. McKenney, & N. Nieveen (Eds.), *Educational design research* (pp. 17–51). London, England: Routledge.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *Journal of the Learning Sciences*, *4*, 39–103.

Kali, Y. (2006). Collaborative knowledge building using the design principles database. *International Journal of Computer-Supported Collaborative Learning*, *1*(2), 187–201.

Kelly, A. E. (Ed.). (2003). The role of design in educational research [Special issue]. *Educational Researcher*, *32*(1).

Kelly, A. E. (2004). Design research in education: Yes, but is it methodological? *Journal of the Learning Sciences*, *13*, 115–128.

Kelly, A. E., Lesh, R. A., & Baek, J. Y. (Eds.). (2008). *Handbook of design research methods in education: Innovations in science, technology, engineering, and mathematics learning and teaching*. New York, NY: Routledge.

Levin, J. R., & O'Donnell, A. M. (1999). What to do about educational research's credibility gaps? *Issues in Education*, *5*(2), 177–229.

Maxwell, J. A. (2004). Causal explanation, qualitative research, and scientific inquiry in education. *Educational Researcher*, *33*(2), 3–11.

Middleton, J., Gorard, S., Taylor, C., & Bannan-Ritland, B. (2008). The "compleat" design experiment: From soup to nuts. In A. E. Kelly, R. A. Lesh, & J. Y. Baek (Eds.), *Handbook of design research methods in education* (pp. 21–46). New York, NY: Routledge.

National Research Council. (2002). *Scientific research in education*. Washington, DC: National Academies Press.

O'Neill, D. K. (2012). Designs that fly: What the history of aeronautics tells us about the future of design-based research in education. *International Journal of Research & Method in Education*, *35*(2), 119–140.

Ormel, B. J. B., Roblin, N. N. P., McKenney, S., 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*, 967–986.

Phillips, D. C., & Dolle, J. R. (2006). From Plato to Brown and beyond: Theory, practice, and the promise of design experiments. In L. Verschaffel, F. Dochy, M. Boekaerts, & S. Vosniadou (Eds.), *Instructional psychology: Past, present and future trends: Sixteen essays in honour of Erik DeCorte* (pp. 277–293). Amsterdam, The Netherlands: Elsevier.

Pickering, A. (1995). *The mangle of practice: Time, agency, and science*. Chicago, IL: University of Chicago Press.

Ryu, S., & Sandoval, W. A. (2012). Improvements to elementary children's epistemic understanding from sustained argumentation. *Science Education*, *96*, 488–526.

Salomon, G. (1996). Studying novel learning environments as patterns of change. In S. Vosniadou, E. De Corte, R. Glaser, & H. Mandl (Eds.), *International perspectives on the design of technology-supported learning environments* (pp. 363–377). Mahwah, NJ: Erlbaum.

Sandoval, W. A. (2004). Developing learning theory by refining conjectures embodied in educational designs. *Educational Psychologist*, *39*(4), 213–223.

Sandoval, W. A. (in press). Educational design research in the 21st century. In R. Luckin, S. Puntambekar, P. Goodyear, B. L. Grabowski, J. Underwood, & N. Winters (Eds.), *Handbook of design in educational technology*. London, England: Routledge.

Sandoval, W. A., & Bell, P. (Eds.). (2004). Design-based research methods for studying learning in context [Special issue]. *Educational Psychologist*, *39*(4).

Scardamalia, M., & Bereiter, C. (1993). Computer support for knowledge-building communities. *Journal of the Learning Sciences*, *3*, 265–283.

Schoenfeld, A. H. (2006). Design experiments. In J. Green, G. Camilli, & P. B. Elmore (Eds.), *Handbook of complementary methods in education research* (pp. 193–206). Washington, DC: American Educational Research Association.

Schwartz, D. L., Chang, J., & Martin, T. (2008). Instrumentation and innovation in design experiments: Taking the turn towards efficiency. In A. E. Kelly, R. A. Lesh, & J. Y. Baek (Eds.), *Handbook of design research methods in education* (pp. 47–67). New York, NY: Routledge.

Scott, T., Cole, M., & Engel, M. (1992). Computers and education: A cultural constructivist perspective. *Review of Research in Education*, *18*, 191–251.

Shavelson, R. J., Phillips, D. C., Towne, L., & Feuer, M. J. (2003). On the science of educational design studies. *Educational Researcher*, *32*(1), 25–28.

Stokes, D. E. (1997). *Pasteur's quadrant: Basic science and technological innovation*. Washington, DC: Brookings Institution Press.

Tabak, I. (2004). Reconstructing context: Negotiating the tension between exogenous and endogenous educational design. *Educational Psychologist*, *39*(4), 225–233.

Van den Akker, J., Gravemeijer, K., McKenney, S., & Nieveen, N. (Eds.). (2006). *Educational design research*. London, England: Routledge.

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

Walker, D. (2006). Toward productive design studies. In J. Van den Akker, K. Gravemeijer, S. McKenney, & N. Nieveen (Eds.), *Educational design research* (pp. 8–13). London, England: Routledge.

White, B. Y. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction*, *10*(1), 1–100.

Zhang, J. (2012). Designing adaptive collaboration structures for advancing the community's knowledge. In D. Y. Dai (Ed.), *Design research on learning and thinking in educational settings* (pp. 201–224). London, England: Routledge.