Design trees: Providing roots for revision in design-based research

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Abstract

This paper introduces design trees as a methodological tool to facilitate design-based research. Traditionally, design-based research is conceptualized as a bridge between theory and practice. Yet, theory rarely specifies practice directly, so this makes documenting revision through design a challenge. In contrast, design trees consider theory and practice as two interwoven strands through five levels of specification: (1) frameworks, (2) principles, (3) conjectures, (4) instruction, and (5) assessment. Each general level constrains, but does not determine, the more-specific levels. As such, researchers need to be explicit about the decisions they make in prospect (i.e. the path they choose along the tree), so that they can follow the path in retrospect in analysis. This supports researchers to contribute to theory and practice systematically. Two case studies, Knowledge Integration and Complex Instruction are used to illustrate design trees.

Introduction

Design-based research aims to contribute simultaneously to theory and practice (e.g., see Edelson, 2002). The logic of design-based research is that if theory is accurately embodied into an artifact or learning environment, then studying practice should provide insights into the theory underlying it (Barab & Squire, 2004). Given the dual aims of contributing to theory and practice, researchers often attempt to link theory to instruction directly. Many studies adopt this *two-level approach* by default (e.g., Barton & Tan, 2009; Birchfield & Megowan-Romanowicz, 2009; Zhang, Scardamalia, Reeve, & Messina, 2009), because this emergent research paradigm still lacks clear guidelines.

The two-level approach assumes a relatively clear distinction between theory and practice. Theory provides a blueprint for practice, which is then enacted. However, most educational theories are too broad to specify practice directly, so research studies often fail to adequately document the evolution of theory through design (cf. Dede, 2004; Ormel, Pareja Roblin, McKenney, Voogt, & Pieters, 2012). Given these difficulties, researchers have argued for the need for new tools to better specify theoretical revision in design-based research (Sandoval, 2014).

To address this need, this paper introduces design trees, a methodological tool which: (1) delineates five levels of specification (frameworks, principles, conjectures, instruction, and assessment), and (2) describes a process for documenting theory and practice at these five levels. Using trees, researchers specify a path from frameworks to assessment. Theory and practice are specified at all five levels, which avoids the traditional split between theory and instruction, allowing researchers to make theoretical and practical contributions at multiple grain sizes. Design trees are first introduced theoretically as a new methodological tool for conducting design-based research. The potential application of this tool is illustrated by analyzing two case studies: Knowledge Integration (Slotta & Linn, 2009), and Complex Instruction (Cohen & Lotan, 1997). These analyses are post-hoc: while design trees provide a useful lens for understanding this work, these projects were not initially developed from this perspective. Rather, the case studies are chosen because they are well-documented in the research literature as interventions, both in terms of theory and impact. By providing design trees as a model in this paper, it will support researchers to enact this practice in prospect as they develop new studies.

Background and Framing

Design-Based Research

Design-based research emerged as a new methodology with the seminal work of Allan Collins (Collins, 1992) and Ann Brown (Brown, 1992) in the early 1990s. During this era, there was a large proliferation of learning technologies, given improvements in the quality and availability of technology. As these technologies were brought into classrooms, there was a need for a corresponding research methodology to study their use. Beyond simply trying to establish if something “works,” researchers needed to know how and why specific tools may result in the desired outcomes so that general principles could be developed to inform revision and the development of future tools. Simultaneously, educational psychology was producing many theories about how learning takes place in laboratory settings. Yet, interventions did not always work as anticipated when they were brought to use in classrooms. In this sense, it was difficult to directly translate theory to practice.

To address these needs, design-based research aims to build theories in context. Just as engineering is seen as a design science that contrasts more basic science (e.g., physics or chemistry), design-based research contrasts the development of context-free theories of learning in laboratory settings. By treating context as an important variable of consideration, rather than something to be "averaged out" through statistical methods, design-based researchers aim to illuminate the relationships between interventions and the contexts in which they operate. By seriously considering the context of implementation, design-based research provides a mechanism for building systematic knowledge by studying practice. Moreover, design-based research also allows for novel environments to be developed and studied, precisely for the purpose of building theory (Howison, Trninic, Reinholz, & Abrahamson, 2011).

Hallmark to design-based research is the notion of iterative design (Cobb, Confrey, Disessa, Lehrer, & Schauble, 2003). Design-based research is seen as taking place through iterative cycles of design, implementation, and analysis. The traditional description of design-based research is now given. To begin, researchers build an artifact or learning environment that embodies certain conjectures about learning (Abrahamson, 2009; Confrey, 2006). Next, the learning environment is enacted (or the artifact is brought into an existing context) and teaching and learning are studied. By studying this learning environment, researchers update their local theory about how learning takes place. As this theory is modified, the design of the learning environment (or artifact) is updated, to reflect changes in the theory of learning. By working through multiple iterations, both theory and practice are refined. The result is a theory of learning that is contextualized, and a practical tool that can be used to promote learning.

Since its inception, design-based research has gained wide interest and acceptance in the learning sciences community, especially following the 2003 special issue of *Educational Researcher* (Kelly, 2003). One of the major appeals to design-based research is the impetus to conduct research that has a practical impact on teaching and learning (Burkhardt & Schoenfeld, 2003; Gutiérrez & Penuel, 2014). More recently, researchers have begun to apply design-based research methods to more complex learning ecologies, such as school districts or national networks (Penuel, Fishman, Cheng, & Sabelli, 2011). While these are promising advances, considering these broader contexts is beyond the scope of this paper, which focuses on classroom-level design.

Despite great interest and potential, design-based research has also received considerable criticism as being underspecified and lacking rigor (cf. Dede, 2004; Ormel et al., 2012). I argue that one of the ongoing challenges for design-based research is that it is typically conceptualized at two levels, focused on the relationship between theory and practice.

The two-level approach

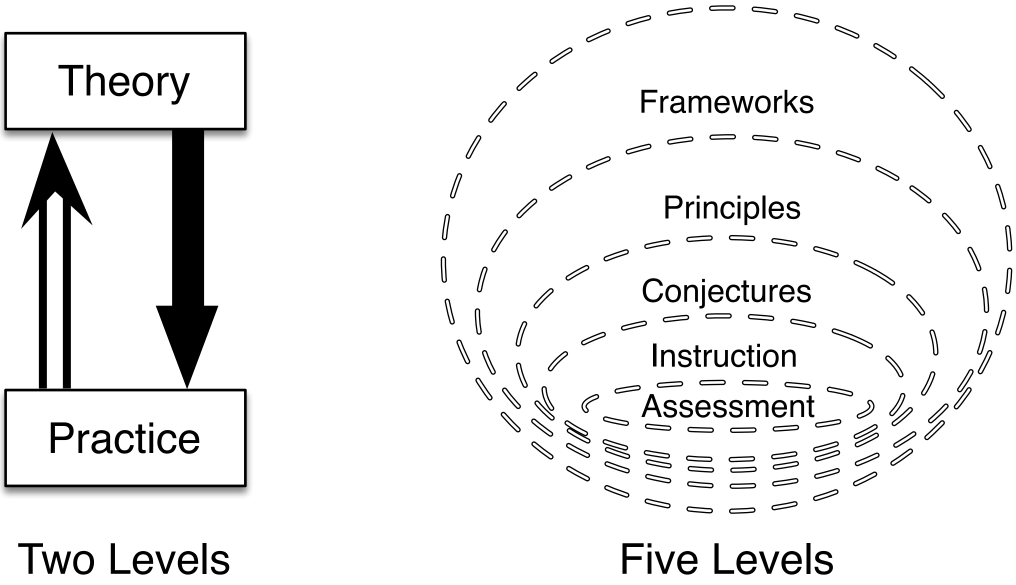
One of the major benefits to design-based research is that it can develop both theory and practice. Yet, this also results in a caricature of how design-based research works, as theory and practice are viewed as two different entities that can be neatly separated. In this caricature, theory is the blueprint, and practice is the enactment of that blueprint. When one enacts the blueprint, it speaks back to the theory, which results in a revised blueprint that is consequently enacted in a new way. In other words, design-based research is conceptualized as a back and forth between a blueprint (theory) and its enactment (practice), which I call the two-level approach.

The prevalence of the two-level approach is evident in reading design-based research studies. In a quick review of recent studies, many adopt this two-level approach by default (e.g., Barton & Tan, 2009; Birchfield & Megowan-Romanowicz, 2009; Hadjerrouit, 2008; Tatar et al., 2008; Zhang et al., 2009). While these studies do provide useful information to the research community, they may fail to rise to the dual charges of building well-grounded theories of learning in context *and* useful learning technologies. A recent review of 18 design-based research reports found that most researchers described how theory informed design, and also reported that re-design resulted in theoretical refinements, but generally failed to specify the rationale and mechanisms for revision (Ormel et al., 2012). I argue that this is not the carelessness of the researchers involved, but rather the lack of adequate tools for describing revision in design-based research. In particular, a two-level approach forces researchers to make direct connections between broad theories and practice, but this is often not possible.

Rather than focusing on the relationship between theory and practice separately, I argue that they should be viewed as two interrelated strands that operate along multiple levels. From this viewpoint, theoretical and practical components of instruction are considered as interrelated, rather than easily separated. This paper argues for at least five levels: frameworks, principles, conjectures, instruction, and assessment. This greater specification helps address concerns that design-based research often lacks: clear connections between theory and practice (Dede, 2004), systematic documentation (Edelson, 2002; Ormel et al., 2012), and an underlying logic of inference, or argumentative grammar (Kelly, 2004). By disentangling theory and practice along five levels (see Figure 1), the articulation and revision of design features is supported in greater detail (cf. Sandoval, 2014).

The use of five levels has a number of benefits. First, it eliminates the need to view theory and instruction as completely separate; instead, both theory and practice can be viewed as distinct but closely intertwined components. Second, it better specifies the multiple grain sizes (or levels) at which research can develop new knowledge. Third, it supports researchers to better specify how theory is used to inform instruction, and vice versa. Rather than making the jump from broad theories down to instruction, which results in tenuous connections between the two, researchers can carefully specify how theory and practice are connected along multiple, smaller gaps. The five-level approach is now elaborated in the context of design trees.

Figure 1. Two and five-level approaches. In the two-level approach, theory feeds directly into practice, which feeds back to theory. In the five-level approach, each level consists of both theory and practice.



Design Trees

This paper proposes a model for design trees with five levels: frameworks, principles, conjectures, instruction, and assessment. Designers begin a study by mapping out their best understanding of theory and practice at all five levels. Moving from general (frameworks) to specific (assessment), a *path* is created between the levels. Each level is embedded in those above it, but not determined by them (i.e. broader theories suggest possible principles but do not fully determine them, principles suggest conjectures, and so on). In this way, each general theoretical specification suggests choices at finer-grained levels, but cannot fully determine them. Thus, the path a researcher chooses is only one of many possible ways to connect various levels within a given theoretical framework (i.e. researchers specify *a* path between levels, but it is not the *only* path between levels). In contrast, the two-level approach implies that theory can specify practice directly (i.e. theories are prescriptive rather than suggestive).

Because broader theories do not specify fine-grained theories directly, it is crucial for researchers to specify a design tree at the offset of the study. This allows them to be explicit about the choices they have made and how they are conceptualizing connections between theory and practice at all levels. Then, later in the study when a design is enacted and analyzed, it is possible to trace the path backwards to make contributions at multiple levels. This a priori specification helps make design-based research a more systematic enterprise.

The five levels of design trees are now described in depth. While this paper provides a method with five levels, it is possible that others may expand the model to contain even more levels of specification (e.g., 6 or 7 levels). The purpose of clearly specifying theory and practice at more levels helps reduce the amount of inference between each set of levels, as exists in the case of the two-level approach.

The Five Levels

Frameworks. At a high level, diSessa and Cobb (2004) identify *frameworks* that guide research. These frameworks provide overarching lenses or perspectives that help guide what researchers attend to. For instance, constructivism draws researchers' attention to cognitive processes (Piaget, 1972), and socioculturalism highlights mediating artifacts and social interactions (Vygotsky, 1980). While these frameworks guide what one attends to, they do not generate specific, testable conjectures, that if rejected would invalidate them (diSessa & Cobb, 2004). For example, socioculturalism frames learning as embedded in social contexts; it is difficult to conceive of an empirical test that would invalidate this perspective. Frameworks may fall out of favor as useful analytic tools, but they are generally only shown as insufficient for understanding certain phenomena, rather than being invalidated outright (e.g., behaviorism; cf. Skinner, 1938). In other words, frameworks generally cannot be tested directly. This is part of the challenge of a two-level approach; frameworks cannot be embodied directly into instruction. Rather, by tracing instruction backwards through multiple levels (i.e. conjectures and principles), design-based research can contribute back to frameworks.

Principles. Beyond focusing one's attention, *principles* specify why aspects of a learning environment are of consequence. For example, principles of explanation specify the role that generalization and reflection play in consolidating understanding (Lombrozo, 2006). Here, the constructivist framework guides researchers to attend to the construction of knowledge, but it is principles that specify the processes through which knowledge construction takes place. Still, these principles fall short of supporting design, as they only describe learning at a general level. For instance, they do not specify the optimal amount of explanation or how to organize learning.

Conjectures. Conjectures embody testable hypotheses about learning to guide classroom engineering (Confrey, 2006; diSessa & Cobb, 2004). These conjectures help researchers connect more general principles about learning into instructional designs. For instance, the "splitting conjecture" relates multiplication, division, and ratio as conceptually distinct from counting, addition, and subtraction (Confrey & Smith, 1995); this implies that improving students' understandings of partitioning, scaling, and similarity should improve their understandings of multiplication, division, and ratio. While this conjecture does not specify instruction directly, it provides a basis for designing instruction. By designing an instructional activity based on this conjecture, it is possible to test and refine this theoretical idea.

Instruction. Conjectures support instruction, but do not specify instruction itself. For instance, the splitting conjecture does not specify which activities will help students learn about partitioning, scaling, or similarity, nor does it specify how much time students would need to spend with such activities to develop an understanding robust enough to improve their knowledge of multiplication, division, and ratio. Moreover, no matter how much instruction is specified from the outset (e.g., by conjectures), its enactment is context-specific; teachers respond to students' current understandings, instruction is embedded into existing classroom structures, and designs often do not work as anticipated. Thus, researchers attend to instruction as planned and instruction as implemented.

Assessment. Learning is not observed directly; assessments only provide evidence of learning. Assessments come in many forms: written vs. verbal, formal vs. informal, focused on process vs. product, cognitive vs. affective, etc. The assessments chosen for a study depend on the types of learning one hopes to observe. For instance, drawing from constructivism, one might attempt to measure student knowledge, whereas drawing from socioculturalism one might instead observe student participation in social practices to see to what extent they are becoming a part of a particular learning community. The choice of appropriate assessments is key to the revision process, because assessments limit what one can "see" as any design is enacted.

The role of practice

As described above, theoretical considerations are used to specify a path between the five levels. Simultaneously, paths consist of myriad practical factors that must be considered. These include: cultural context, curriculum sequencing, classroom context, prior content knowledge, learner dispositions, beliefs about learning, intuitive experiences, affect, vocabulary, language ability, item difficulty, mode and medium of assessment, and the grouping of students. Which factors are relevant depends on the design level. At the level of assessment, fine-grained details such as vocabulary, item difficulty, and wording are of great consequence. Yet, at the level of conjectures, other factors such as the grouping of students and learner dispositions may be more relevant. Similarly, when looking at frameworks or principles of learning, cultural context and curriculum sequencing may be considered. For instance, for students to build from prior learning experiences (constructivism), instruction must be designed around something culturally relevant. If not, the design may fail due to a large overarching flaw, and thus never have an opportunity to contribute to theory and practice at finer levels of specification; this “broken link” near the base of the design tree may inhibit the theoretical and practical contributions that the design can make at all higher levels (i.e. the path becomes cut off near the level of principles, so it never has a chance to contribute to conjectures, instruction, or assessment).

The application of design trees is now considered in two case studies: Knowledge Integration and Complex Instruction. These case studies show how design trees can be used from a historical perspective, to systematically describe the revision of theory and practice in a complex design-based research project. In this way, design trees provide an analytic framework for researchers to understand existing studies. As researchers analyze existing cases in a systematic way, it can help them better understand the design and revision process in a way that influences future studies. Nevertheless, the true potential of design trees is only realized in prospect, because they provide an overarching structure for planning and analyzing design-based research studies. This paper provides the framework, described in detail with existing cases, so that other researchers may use it to plan, implement, and analyze their own projects, thus developing a common practice and methodology for design-based research.

Knowledge Integration

Knowledge Integration (KI) provides the backbone for the Web-based Inquiry Science Environment, WISE. WISE is a technology-enhanced learning environment for supporting inquiry-based learning in science, developed over multiple decades (Slotta & Linn, 2009). WISE is a freely available, Internet-based curricular platform that provides learning tools and allows for student work to be collected for assessment. In the context of WISE, KI provides coherence among the research base, instructional tools, and assessments. WISE boasts a large user base, and has been applied to settings ranging from middle school science to college engineering. In a comparison study consisting of 8232 students in 16 schools across five states in the US, researchers found that students who were taught using WISE produced significantly better explanations than those who did not (Linn, Lee, Tinker, Husic, & Chiu, 2006). WISE has been written about in many dozens of research articles and a number of books. As such, the theoretical and practical components of KI are well-documented, making it a powerful case for exemplifying design trees. The following descriptions draw heavily from *WISE Science: Web-Based Inquiry in the Classroom* (Slotta & Linn, 2009). This design tree as presented represents decades of theoretical and practical work; it differs from the less-refined versions that implicitly existed throughout the history of KI's development. After presenting the current versions of the tree, an example of how the tree came to be is given.

Theoretical Specification

The underlying premise of KI is that a robust understanding of science requires students to connect multiple ideas (i.e. integrate them) to explain science concepts. KI provides the backbone for WISE, and can be understood at multiple levels of theoretical specification.

Frameworks. KI is grounded primarily in constructivism, focused on the cognition of individuals and groups of students. KI relates to constructivism, as knowledge is considered as something that students "build" through reflecting on learning activities, rather than something that "enact" through participation in social practices. To build on student's prior knowledge, WISE units connect students' everyday experiences with normative science ideas. Although WISE units attend to social processes (e.g., student collaboration), they are not a central focus. As such, if WISE were to adopt a sociocultural framework, it would emphasize concepts such as: status, power, and distribution of participation. This framework is not necessarily "better" than constructivism, but it would provide different foci of attention.

Principles. There are four main theoretical principles to KI: (1) learning should be accessible (i.e. personally relevant), (2) thinking should be visible, (3) learning should be collaborative, and (4) learners need autonomy. In general, adhering to these principles *should* support students' KI. To make learning accessible, WISE uses relatable contexts, like global climate change and Internet literacy. WISE avoids highly-idealized environments (e.g., frictionless surfaces), which can be difficult for students to make sense of (Clement, 1998). Making thinking visible (Collins, Brown, & Holum, 1991) involves using simplified models to build conceptual understanding (Edelson, Gordin, & Pea, 1999), and requires understanding how models make ideas visible through assessment (Linn & Hsi, 2000). Collaborative learning focuses on how social environments provide opportunities for students to learn from their peers (Scardamalia & Bereiter, 1994). Finally, WISE emphasizes learner autonomy, which has myriad long-term benefits for student learners (Bandura, 1989). In WISE, learners build on their prior knowledge, test hypotheses, and reflect on their learning. Ultimately, students develop tools and processes for lifelong learning.

Conjectures. The primary conjecture in the WISE platform is that KI is best supported through a four-step process: (1) elicit ideas, (2) add new ideas, (3) develop criteria, and (4) sort out ideas. Unlike more general principles of making learning accessible and making thinking visible, this conjecture comes closer specifying instruction that can be tested. For example, if "adding new ideas" is indeed a key step for KI, by designing comparative instructional sequences, one that involves adding ideas and one that does not, such a conjecture can be tested. Or, one could develop alternative instructional sequences that build on these processes in a different order and study the results.

KI begins with eliciting student ideas to interrogate and build upon them (elicit ideas). Ideas are elicited from many students, so that they can be compared and contrasted. Next, new ideas are added to the learning environment, so that students can work to negotiate and integrate these multiple, and sometimes conflicting, meanings to build normative science understandings. Next, students develop criteria to distinguish between these ideas (develop criteria). Not all ideas are equally valid from a scientific perspective, so KI-driven lessons help students determine how distinguish the quality of such ideas. Finally, students sort out ideas. The supposition is that learning takes time, and non-normative ideas are not easily "replaced" by normative understandings. Rather, students need time to refine partial understandings through appropriate activities (sort out ideas). Taken together, these four aspects of KI can be used to develop lessons that follow this process, but there are still many ways in which this account of learning can be crafted into instruction. As such, WISE has many different KI-aligned instructional sequences.

Instruction. WISE units are organized into nearly a dozen "effective instructional patterns," built around KI. These instructional patterns represent different ways to enact the four-part sequence above. They generally fall into one of three curriculum unit types: (1) critique projects (evaluate scientific credibility of resources), (2) debate projects (use evidence to construct and evaluate arguments), and (3) design projects (apply activities to design a solution). WISE supports units with an array of over 20 tools, including: WISE journal, Reflection notebook, and Inquiry tools, such as the data visualizer (presents tables and graphs), sensemaker (students sort evidence into arguments), and causal map (arrange causes into an interactive concept map). These tools and approaches have been revised over numerous experiments, refined to support the project's conjectures about how learning takes place.

Assessment. To measure KI, WISE uses a six-level rubric (TELS, 2011), which focuses on the "relevance" of student ideas and the connections made between them. The lowest three levels – irrelevant, isolated, and partial – are scored when student ideas are not connected. The next three levels – basic, complex, and systematic – are scored when students link one (basic) or two (complex) scientific ideas, or when they compare or contrast contexts, applying relevant examples in each case (systematic).

Theoretical revision: A case study

The five levels of theoretical specification described above were developed over decades of careful research. To better understand how such a refined theory emerges, consider the early stages of WISE, drawing from the Computer as Learning Partner (CLP) project (Stern, 2000). The case study considered is of the E-Lab Notebook (Stern, 2000). When discussed in this case study, levels are denoted in *italics*.

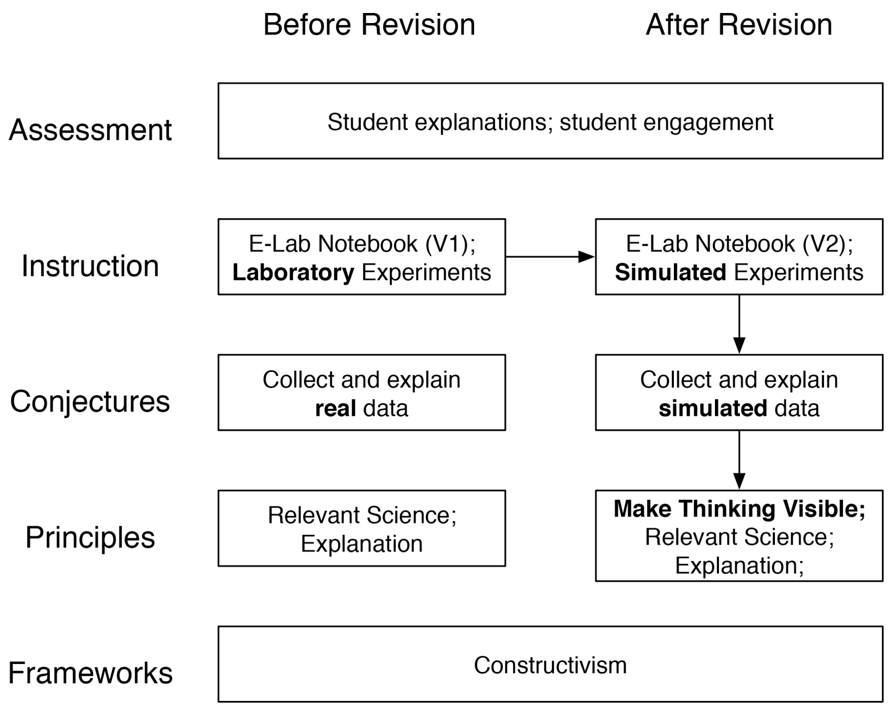
From its inception, WISE was grounded in a constructivist *framework*. In this early work, CLP drew on *principles* about (1) the relevance of science to students and lifelong learning and (2) explanation in learning (Lombrozo, 2006). Based on prior research, the researchers *conjectured* that actually collecting data and explaining it would help support KI. At the level of *instruction,* the E-Lab Notebook was designed to facilitate student data collection, analysis, and explanation. The actual student explanations and studies of student engagement were *assessments* to determine the impact of this work. The practical components of the design were informed by years of experience of the design team. For instance, the designed environment aimed to: encourage reflection, help students focus on relevant features rather than extraneous details, help students see similarities between situations, and encourage conclusions based on sufficient data. These practical goals were seen as required to support the hypothesized theoretical processes of KI. These principles informed the user interface elements of the E-Lab Notebook, as described in more detail elsewhere (Stern, 2000).

Initially, the E-Lab Notebook was used for laboratory experiments, consistent with constructivism and making science relevant through hands-on experiences. However, students struggled to generalize from the laboratory to other everyday experiences. Given this observation, the team instead introduced simulations for experimentation rather than actual lab experiences, and found positive results. This helped the team revise its *conjectures* about learning. Theoretically, it appeared that it was not required that students actually collect real-world data for analysis. Rather, generating data through a simulation seemed to be more productive. In particular, simulations helped make scientific processes explicit in a way that was not always possible in the lab (e.g., visualizing invisible interactions in thermodynamics). This informed a revision to *principles*, and marked the emergence of the idea "making thinking visible," which is now a cornerstone of the WISE platform.

There were also practical revisions to the E-Lab Notebook, grounded in classroom observations of (for instance): (1) student successes and struggles with the reflection tools, (2) students ignoring data while writing explanations, and (3) students not wishing to express minority opinions. The *instructional* tools were refined to address these practical limitations. For instance, by allowing students to view their data while writing explanations, students were much more likely to incorporate data in their explanations. Similarly, the implementation of agreement bars allowed individual students to express agreement with the group explanation, which facilitated discussion within groups. These practical changes further supported learning through explanation, but did not refine the theory itself. Additional information about the development of the E-Lab Notebook is given elsewhere (Stern, 2000).

This analysis is necessarily post-hoc, because the WISE project did not develop with the guidance of design trees. Nevertheless, this example does illustrate how a path from frameworks to assessment can be created using theoretical considerations, and that the testing of instruction can speak back to theory and practice at multiple levels (principles, conjectures, and instruction, in this example). As researchers engage in multiple studies, they are able to continually refine theory and practice along multiple levels of the specified path. For researchers who use design trees from the offset, this can be a particularly useful tool because it forces the team to be explicit about theoretical and practical commitments, which highlights the potential areas for revision. The revision of the KI design tree is given in Figure 2.

Figure 2. Revision of the KI design tree.



Complex Instruction

Complex Instruction (CI) is a set of techniques for promoting equity in heterogeneous group work (Cohen & Lotan, 1997). CI emerged from decades of sociological research on inequity in heterogeneous classrooms. The underlying logic of CI is that status imbalances in the classroom lead to differences in opportunities to learn, which ultimately result in inequitable learning outcomes. As a corollary, if status imbalances can be "treated," then learning outcomes should be much more equitable. Over a number of studies in different contexts, researchers have found that the use of CI produces statistically significant learning gains for all students, and that the "lowest status" students show the largest gains (Cohen & Lotan, 1997).

CI provides a useful contrast to KI to exemplify design trees. First, because CI is grounded in socioculturalism, rather than constructivism, it results in a design tree with very different theoretical specifications. Second, CI is a set of instructional techniques that can be used with many different curricula, whereas KI tends to operate more at the level of curriculum through WISE. Third, CI requires limited use of technology whereas KI is used in highly technology-dependent environments. As such, this example illustrates how design trees can be applied across a variety of settings.

Theoretical specification

In what follows, I describe the five levels of specification for CI.

Frameworks. CI draws primarily on socioculturalism (Vygotsky, 1980), which views learning as a process of participating in social practices in increasingly sophisticated ways (Lave, 1996). Thus, the primary consideration for CI is how students become competent at participating in valued disciplinary practices (Engle, 2012). The ability to engage in these practices (e.g., problem solving, argumentation) is taken as a sign of competence. This differs from constructivism, which focuses much more on the knowledge that one "constructs" through reflection. Nevertheless, the ability to "show one's understanding" for instance, on a standardized test, is still a real consideration in the context of CI, due to the social justice implications of demonstrating one's "knowledge" on a standardized test.

Principles. The goal of CI is to promote high-functioning group work so that all students can learn to meaningfully engage in disciplinary practices. Through a detailed study of practitioners who were very competent with CI (Nasir, Cabana, Shreve, Woodbury, & Louie, 2014), five principles seemed to emerge: (1) all teachers and students are learners, (2) working from strengths makes space for vulnerability, (3) redefine "smart," (4) redefine school math, and (5) relationships are crucial. In other words, students need a safe space where they can engage in meaningful mathematical work. These general principles help guide the ways in which one might enact specific instructional techniques. At a theoretical level, these ideas can be understood through a number of constructs such as: influence (Engle, Langer-Osuna, & Royston, 2014), positioning (Davies & Harré, 1990), power (Foucault, 1977), and status (Cohen & Lotan, 1997). These constructs give meaning to concepts of equity and inequity in small group interactions, which helps describe learning processes. To promote equitable learning, power imbalances need to be managed, so that all students can have more equal status.

Conjectures. CI conjectures a number of possibilities for creating an equitable group learning environment. Of particular relevance are the ideas about equalizing status. The first idea is that if students are given multiple meaningful ways to interact with a task, a wider range of students are more likely to have a way to contribute and develop status. Similarly, CI posits that certain acts of positioning can be used to either elevate or diminish the status of students within a classroom. These acts can happen both intentionally and incidentally (Langer-Osuna, 2016). Crucially, these acts of positioning should be visible in the classroom space, rather than private.

Instruction. The above conjectures about status equalization suggest possible instructional techniques for equalizing status. One of these is the multiple ability treatment, which involves framing tasks as requiring multiple skills, which all students will have some of but none will have all of, so cooperation is required. "Status interventions" are discourse moves that involve elevating or "assigning" status to low status students (e.g., publicly praising their contributions) to reduce imbalances in status. Teachers can organize activities within their classroom as such to create opportunities for such interventions (e.g., having small group work time that leads into plenary discussion, where contributions can be highlighted publicly).

Assessment. Given CI's sociocultural commitments, the actual study of student participation is a major source of assessment. This involves studying students as they work and seeing if CI can be used to shift who participates and how. Assessment might also include student perceptions of status, such as through sociometric surveys. Finally, the distribution of student outcomes on any type of assessment might be used, to see if CI really does help reduce imbalances.

Theoretical revision: A case study

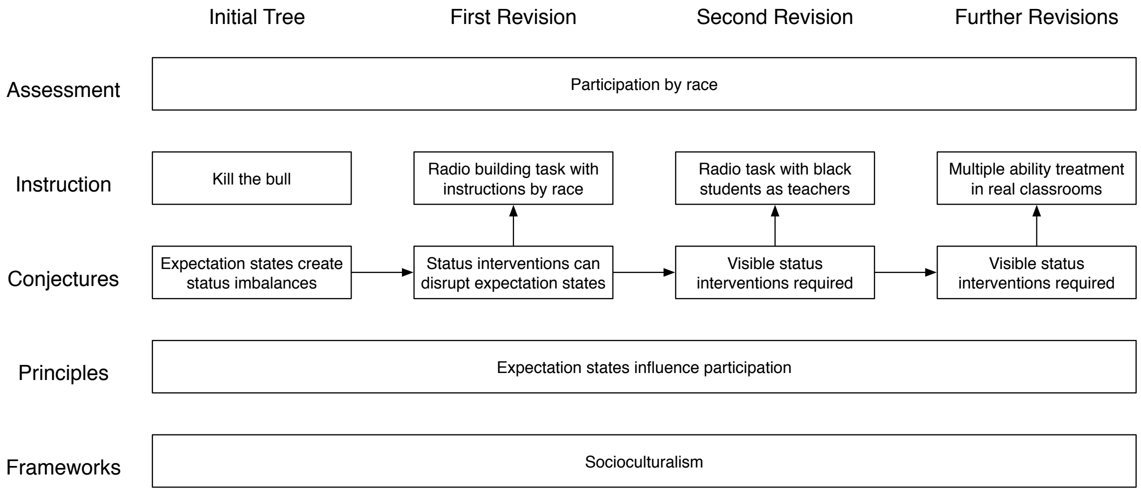
Once again, these five levels were developed over decades of research. The following case study describes multiple examples of how this theory emerged over time.

CI has its roots in sociological and organizational theory (sociocultural *frameworks*). The genesis of CI as a theory and set of techniques can be traced back to status characteristics theory (Berger, Cohen, & Zelditch, 1972). In short, this theory posits that age, sex, race, and other visible markers impact actors' "expectation states," which influence how participation, status, and prestige are distributed amongst members of a group. To test these theoretical *principles*, researchers developed a simple *instructional* game called Kill the Bull, in which players had to make collective decisions about how to proceed on a game board (Cohen, 1993). This game was designed to set up possible expectations and observe if actors behaved as expected. The researchers set up interracial groups to play this game, and as expected, in 14 of 19 games, white actors were the most active.

Expectation states theory *conjectured* that status imbalances resulted when expectation states were activated in a social situation. As such, if expectation states could either be altered, or if their activation could be avoided altogether, one would conjecture that inequities would be reduced. To test this conjecture, researchers created an (*instructional)* environment in which interracial groups of four were instructed to build a radio (Cohen, 1993). A key feature of this environment is that it was possible to *assess* the relative contributions of different participants. In this experiment, black participants were given "better" instructions than white participants, and group interactions were subsequently studied. This was an early *instructional* embodiment of a "status intervention." Yet, white participants still dominated the conversations. As a result, the researchers updated their *conjecture*, concluding that the act of assigning status needed to be visible to all participants. This implied that different *instructional* techniques would be required for assigning status, because the must be visible to (and understood by) all participants.

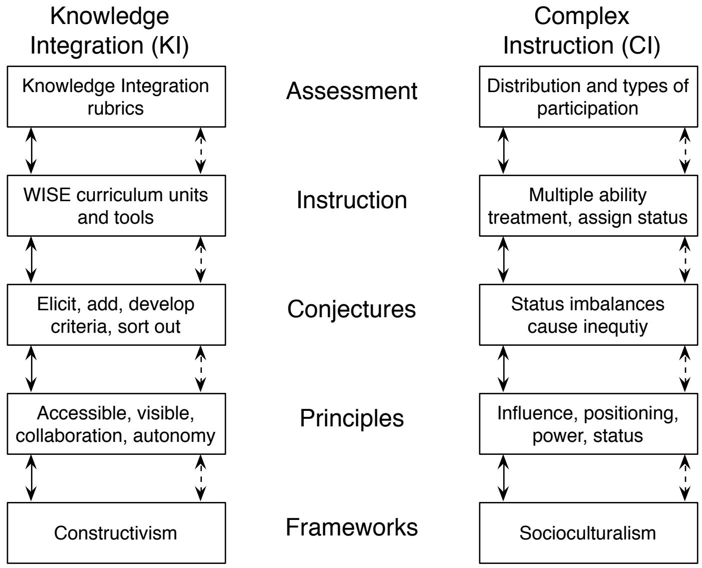
Using this revised conjecture, a follow-up study was developed, in which black students were positioned as teachers of the white students in building the radio (Cohen & Roper, 1972). In this context, the positioning of black students as competent was made clear to all students (because they were positioned as teachers), and as a result, participation between white and black students was approximately equal. A number of follow up studies were conducted using similar ideas, and ultimately the multiple ability treatment was developed as an *instructional* technique, which was later studied in real classroom settings. The process of revision is illustrated in Figure 3.

Figure 3. Revision of the CI design tree.



As this brief case study highlights, the researchers began with general theoretical principles about expectations, which they began to test in increasingly sophisticated ways. Over these multiple tests, theory and practice were refined and a set of useful instructional techniques emerged. A comparison of relatively-developed KI and CI design trees is given in Figure 4.

Figure 4. A comparison of KI and CI design trees.



Summary

Design-based research is a promising methodology that is now widely recognized by the educational research community. Over the past two decades, a number of efforts have been made to systematize design-based research, improving its usefulness and rigor (e.g., diSessa & Cobb, 2004; Sandoval, 2014). Design trees contribute to this systematization, in two main ways: (1) they help specify research at five (or more) levels, and (2) overcome the challenge of focusing on theory and practice as two separate components. In addition, design trees can be used to complement other methods for making design-based research more systematic, including:

ontological innovation (diSessa & Cobb, 2004), problem analysis (Edelson, 2002), the learning design perspective (Gravemeijer & Cobb, 2006), conjecture maps (Sandoval, 2014), and learning trajectories (Penuel, Confrey, Maloney, & Rupp, 2014).

Specifying five levels supports the documentation and refinement of design decisions in more depth, and helps draw attention to the number of different levels at which theory and practice operate. In contrast, the gaps between theory and practice in the two-level approach are too large to support meaningful planning. Moreover, specifying theory and practice as levels, rather than as operating at multiple levels, obscures that there are a number of levels of both theory and practice. As such, design trees support both the planning of design-based research projects *and* the actual revision of designs by further specifying the design process. This helps address concerns for the need to further specify design-based research (Dede, 2004; Kelly, 2004) and improve documentation and reporting (Edelson, 2002; Ormel et al., 2012). Moreover, this approach highlights the importance of practical considerations, which are often underemphasized. Doing so helps make the research more transparent, and also provides opportunities to see the development of new theoretical ideas that emerge from practical considerations. It also helps researchers distinguish which of their contributions are theoretical and which are practical.

The two case studies in this paper show the application of design trees in historical settings. In the KI case, researchers began with a basic notion of constructivist learning through *principles* of explanation. An important *conjecture* about the learning process was that students needed to learn through real laboratory experiments, rather than simulation. Yet, through revision, the researchers found that *instruction* built around simulations was actually more effective on the target *assessment* of student explanations and engagement. By applying design trees in this scenario, researchers can see that revisions took place at multiple levels, and that the study helped develop new underlying *principles*. As an alternative, suppose that the two versions of E-Lab Notebook were simply compared wholesale, and one was viewed as “better” than the other. While this may be true, it makes it much more difficult to extract systematic knowledge from the study. Indeed, the development of particular theoretical *principles* has allowed the WISE project to build numerous productive *instructional* sequences around KI, rather than simply applying a single tool (E-Lab Notebook) to each scenario.

In the CI case, researchers created a variety of *instructional* sequences to study principles from expectation states theory. In contrast to the KI case, the *instruction* used here was simply a means to refine *conjectures* that could later be applied to real classrooms; developing the best radio building task was not a goal of the work. Over a number of iterations, the multiple ability treatment came about. Here, design trees are informative because they allow a researcher to see how small differences in the *conjectures* about disrupting expectations states played out differently in a variety of *instructional* contexts. In this way, researchers and practitioners develop insight into the nuances of using the multiple ability treatment that might otherwise not be evident. For instance, a teacher might use the technique in a way where the intervention is not sufficiently visible to all students, thus rendering it ineffective.

These case studies show how design trees can be used to systematically describe the revision of theory and practice in a complex design-based research project, providing greater insight for researchers and practitioners. Nevertheless, these are post-hoc analyses, and as such do not truly capture the potential of design trees, which is that they provide an overarching structure for planning and analyzing design-based research studies. As other researchers adopt this structure and use it for planning and analyzing their projects, it will provide a common language for understanding and comparing various designs. Over time, reporting using trees could contribute to the continued development of methods for making design decisions. In doing so, it will support designers in developing a common practice and methodology for design-based research.

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