**Paper Title** Conjecture Mapping: An Approach to Conducting Design-Based Research With Embedded Co-Design Cycles

**Author(s)** Amanda Peel, Northwestern University; Jacob Kelter, Northwestern University; Lexie Zhao, Northwestern University; Michael S. Horn, Northwestern University; Uri J. Wilensky, Northwestern University

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**Purpose**

This is a *methodology paper* that describes our approach to conducting design-based research (DBR) with conjecture mapping (Sandoval, 2014). DBR is the study of learning through the design, implementation, and subsequent study of innovative learning experiences and instructional strategies (Brown, 1992; Collins, 1992; Design-Based Research Collective, 2003). Conducting DBR allows researchers to work with educators to learn about how, why, and when new learning environments work in real-world school settings (Design-Based Research Collective, 2003). Iterative cycles of design, enactment, analysis, and redesign are central to DBR methodologies (Cobb, 2001, Cobb et al., 2003; Collins, 1992).

In our work, we leverage iterative conjecture mapping to frame embedded design cycles for two audiences: teachers and students. One design cycle focuses on professional development (PD) to support computational thinking (CT) integration and teacher outcomes. During our PD, we work with teachers to iteratively co-design new CT-integrated science and math units for their secondary classrooms. For both teacher- and student-facing design cycles, we use iterative conjecture mapping, which frames each DBR step: design, implementation, evaluation, and revision of the intervention. We argue conjecture mapping can be used to connect teacher and student outcomes through embedded design cycles.

**Framework**

Conjecture mapping provides a method of investigating causal processes of how designs support desired outcomes through explicit focus on interactions with design elements (Sandoval, 2014). Conjecture maps consist of *high-level conjectures* (initial ideas about supporting learning through the learning environment), *embodiment* (the learning environment design elements), *mediating processes* (the activities and/or interactions connecting the embodiment and desired outcomes, and *outcomes* (the desired outcomes of the learning environment). The elements of the conjecture map form pathways connecting the design of a learning environment to the desired outcomes. This mapping provides a way to explicitly support both the design process and the evaluation of the resulting design. Table 1 depicts an example conjecture map for a professional development to support teacher integration of computational thinking with science and math.

**Methods**

We utilize conjecture mapping design cycles to identify desired outcomes, design the learning experience (e.g., PD, student unit) to achieve those outcomes, implement the learning experience (and collect data), analyze the learning experience, and revise the learning experience. This methodological approach features multiple rounds of qualitative coding with triangulation between data sources (Miles et al., 2014). To begin, designers develop an initial conjecture map to plan and design the learning experience, starting with the desired learning outcomes for participants. Next, designers iteratively design and build the conjecture map. As design elements (embodiments) are created, they should be added to the map with how they are anticipated to support the desired outcomes (mediating processes). The connections between embodiments, mediating, processes, and desired outcomes form the initial conjecture map of the design of the learning experience. Table 1 depicts an initial conjecture map from our work. During the design, it is important to design data collection to take place during the learning experience implementation. Data should be collected to elucidate outcomes and mediating processes and how they are connected to each other and the embodiment.

In the next step, designers implement the learning experience and collect data. Then, designers use the data collected to test the anticipated outcomes, mediating processes, and connections and create a revised conjecture map that reflects the data. In the first round of coding, designers investigate data sources from the implementation to identify outcomes that were measured through the learning experience, which may or may not match the intended outcomes. Next, designers code the data for connections between the identified outcomes and specific design elements (embodiments) and how they led to the outcome (mediating processes). For example, in our work, we found teachers learned about CT from engaging in lessons as a student and answering questions during our workshops (Figure 2, Table 4). These findings can be used to modify the conjecture map so it represents the actual learning experience implementation (Table 2). A third round of coding is done to identify issues and areas for improvement that arose during the learning experience implementation. It is important to connect issues to existing mediating processes and embodiments in order to improve these areas in the redesign phase.

The refined conjecture map is then used to redesign the learning experience. If outcomes were initially desired but not achieved, designers should design new embodiments to engage participants in new mediating processes to support the desired outcomes. Additionally, the issues identified should be addressed in the redesign in order to avoid unwanted outcomes. The redesign begins the second cycle of conjecture mapping design research. As before, the learning experience is designed, or redesigned, implemented, and assessed using the conjecture mapping approach. We argue that learning experience design is incomplete without the implementation, assessment, and data-informed redesign. The full depth of learning experience design and design-based research can be explicitly explored with the conjecture mapping cycles approach.

**Embedded design cycles.** We use iterative design cycles to conduct design-based research (Cobb et al., 2003) on professional development (PD) for teachers and learning interventions for students. These two design goals are depicted as embedded design cycles (Figure 1). The outer design cycle (depicted in red) focuses on designing, implementing, analyzing, and revising a PD for teachers to support CT integration. Within the PD, we engage with teachers in another design cycle (black) to co-design new CT-integrated science and math units, which are then implemented, co-analyzed and co-revised. We have now completed two cycles of these embedded design cycles (Authors, 2020; Authors 2021). The PD design cycle focuses on teacher outcomes, while the embedded CT-integrated unit design cycle focuses on student outcomes. This unit design cycle is carried out by researcher-teacher teams where teachers and researchers work together to co-design, implement, co-analyze, and co-revise units. The design and analysis methods described above are utilized in both cycles. In the PD design cycle, researchers take the role of designers, and in the unit design cycle, teachers and researchers take the role of co-designers. This embedded approach allows researchers to design multiple outcomes levels (i.e., students and teachers) with one project. The embedded approach aligns student outcomes with the PD, which we argue connects teacher learning with classroom-ready applications, which, when implemented, support student outcomes.

**Results: An example of the methodology in use**

This section will provide examples from our work utilizing this methodology. Due to space limitations, we focus on the PD design cycle, but examples from both cycles will be presented in the conference session.

**PD Design Cycle.** The design of our four-week PD was guided by our initial conjecture map (Table 1). During the first week, teachers participated in several workshops aimed to help them understand CT and its integration with science and math. In the subsequent three weeks, each teacher worked with one researcher to co-design new CT-integrated science and math units. Data sources included weekly reflection forms and discussions, a post-PD survey, a post-PD interview, and recordings of PD sessions. These data sources were analyzed with the conjecture mapping coding approach.

*Teacher Learning Outcomes.* Three teacher self-reported outcomes were identified through the qualitative analysis: 1) Learning about and how to use CT tools, 2) Learning about pedagogy to support CT integration and scaffolding, and 3) Changes in values and attitudes regarding CT. Table 3 shows examples of quotations coded for each outcome. These results indicate the PD resulted in positive outcomes in terms of teacher learning and shifts in values and attitudes.

*Design mediated outcomes.* The initial conjecture map was refined based on teacher responses, and then used to investigate the connections between outcomes and the PD design (Table 2). The *Embodiment* column describes the workshops and co-design teachers engaged in during the PD. The *Outcomes* column shows the outcomes identified from the data in the prior section. The *Mediating Processes* column describes the processes teachers engaged in during the embodiment that led to the outcomes.

Four mediating processes were identified within the data: 1) Answering questions in the CT-STEM units, 2) Interacting with computational tools, 3) Discussions, and 4) Designing and creating computational tools. The video data provided evidence of connections between mediating factors and outcomes, thus triangulating the various data sources. Figure 2 depicts those connections with numbered arrows, and Table 4 contains examples of video data for each connection.

The connections between mediating processes and outcomes indicate, based on qualitative data, that the design of the PD led to teacher learning and changes in values and attitudes regarding CT. The overall conjecture map led to the development of two major conjectures about the design of the PD. First, teacher engagement in workshops as learners followed by explicit reflection leads to learning about CT and changes in perceptions of CT. Second, co-design allows for learning about CT and changes in perceptions of CT.

Although the PD was a success and led to several important outcomes, teachers did experience challenges and tensions. Some teachers felt unprepared to pick a unit topic after the first week. Teachers felt that workshops and design time could have been better interwoven to allow for reflecting on how to incorporate the ideas in their context. Table 5 shows the revised conjecture map that was used to design the PD for the following year (2020). To address challenges, we began co-designing and planning earlier in the PD and allowed for reflection and planning with each workshop. To facilitate discussion and feedback, we added several sessions where teachers discussed their units with each other and with STEM professionals outside the project. After implementing and assessing the 2020 implementation, we are currently designing the 2021 PD, in which we plan to support teacher analysis and revision of their co-designed units.

**Unit Co-Design Cycle.** In the student-facing design cycle, teachers work with our team during the PD to co-design new CT-integrated science and math units. In the 2021 cycles, we will use the conjecture mapping approach to support the full unit co-design cycle (co-design, coimplement, co-assess, co-redesign, repeat) with our teacher partners. In past cycles, teachers co-designed units, implemented their units with our support, and modified their units based on anecdotal experiences and unstructured assessment of student work. This year we will explicitly support the co-analysis and co-revision process with conjecture mapping. We will work with teachers to engage in conjecture mapping for their co-designed units. Teachers will analyze student work to assess their 2020 units and create a conjecture map that will be used to support co-redesign. Our initial desired student outcomes can be seen in Table 6. We predict the process will help connect intended outcomes to unit embodiments and pedagogy relating to CT integration. Data from this cycle (summer 2021) will be presented at the conference.

**Scholarly Significance**

This methodology has implications for design-based research that connects teacher-facing and student-facing learning experiences. The methodology explicitly supports intervention design, implementation, analysis, and revision within embedded design cycles, one for designing PD and one for co-design of student units. Conjecture maps allow for designers (researchers and teachers) to develop learning experiences that support learning outcomes through explicit attention to design embodiments and mediating processes. This approach expands Sandoval's conjecture mapping (2014) into a methodology of embedded cycles for designing teacher- and student-facing learning experiences. Additionally, this approach shows how the development of multiple maps can explicitly connect student and teacher outcomes, which could support more sustainable change in practice (Fishman et al., 2013). If teachers co-design, implement, co-analyze, and co-revise their student units within the context of a PD, the teacher and student learning goals become explicitly aligned. We argue this embedded co-design within PD design supports uptake of curricular reform ideas because through the PD, teachers learn about a new approach, design with the new approach, enact their design, learn to analyze their design, and revise their design. The PD completes the design cycle, supporting teacher ownership of classroom materials from design through revision, which we believe supports multi-year implementation of the new approach. Meanwhile, researchers analyze the entire process and revise it to better support teachers and students.

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Blinded for review

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**Figures and Tables**

Table 1. Initial PD Conjecture Map About the Design of the 2019 PD

| **Conjectures** | **Embodiment** | **Mediating Processes** | **Outcomes** |
|---|---|---|---|
| Teacher engagement in workshops and co-design will lead to learning about CT and how to integrate CT. | Workshops in which teachers participate in lessons about CT. | Interacting with computational tools | Learning about CT & computational tools |
| | Co-design in which teachers worked with researchers. | Designing and creating computational tools | Learning about how to integrate CT |

Table 2. Revised 2019 PD Conjecture Map

| **Conjectures** | **Embodiment** | **Mediating Processes** | **Outcomes** |
|---|---|---|---|
| Teacher engagement in workshops as learners followed by explicit reflection leads to learning about CT and changes in perceptions of CT. | Workshops in which teachers engaged as learners. | Answering questions in the CT-STEM units | Learning about and how to use CT Tools |
| | Workshops in which teachers reflected on pedagogy, CT content, and science content. | Interacting with computational tools | Learning about pedagogy to support CT integration and scaffolding |
| Co-design allows for learning about CT and changes in perceptions of CT | Co-design in which teachers worked with researchers. | Discussions | Changes in values and attitudes regarding CT |
| | | Designing and creating computational tools | |

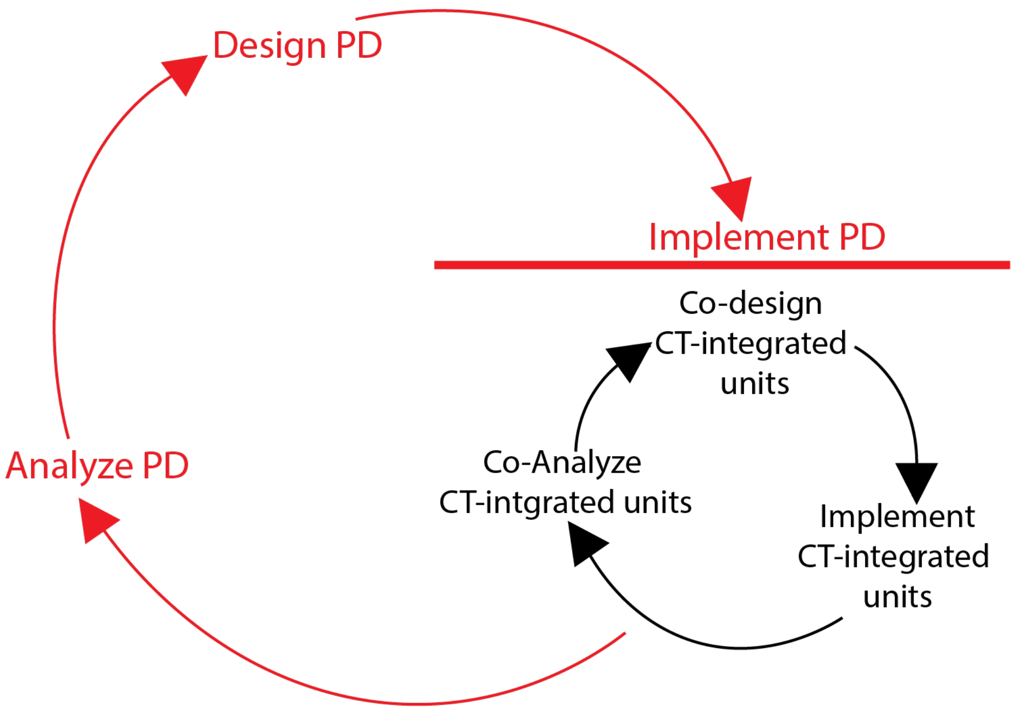


Figure 1. Embedded Professional Development and Student Unit Design Cycles

Table 3. Teacher Learning Outcomes

| Outcome | Quotation Example |
|---|---|
| Learning about and how to use CT tools | "The breakouts on Python, CODAP, and NetTango were very informative. Gave me something to think about moving forward" (Nate, Week 2 Exit Ticket).<br><br>"I learned a lot about how to program NetLogo, as well as how to use various computational tools effectively in instruction" (Derick, Post CTSI Survey). |
| Learning about pedagogy to support CT integration and scaffolding | "Learned more about the use of CT in my classroom, how to incorporate more CT in my class and how I may already be using it" (Lisa, Week 1 Exit Ticket).<br><br>"Brainstormed new ideas for modeling the unit, interesting ideas for models that I wouldn't have thought of, like pulling in the data snapshots to model and having students place sensors" (Lacey, Post CTSI Survey). |
| Changes in values and attitudes regarding CT | "I have really learned a lot and will be more confident using CT with the students. I think I may even be able to do |

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| | a little trouble-shooting and be less reliant on the team that observed my classes." (Tracy, weekly reflection 7/25)<br><br>"CTSI also gave me a different perspective on teaching high school statistics. I realized that, in the past, I was not giving my students exposure to the types of thinking (and technology) used by actual data scientists" (Jeremy, Post CTSI Survey). |

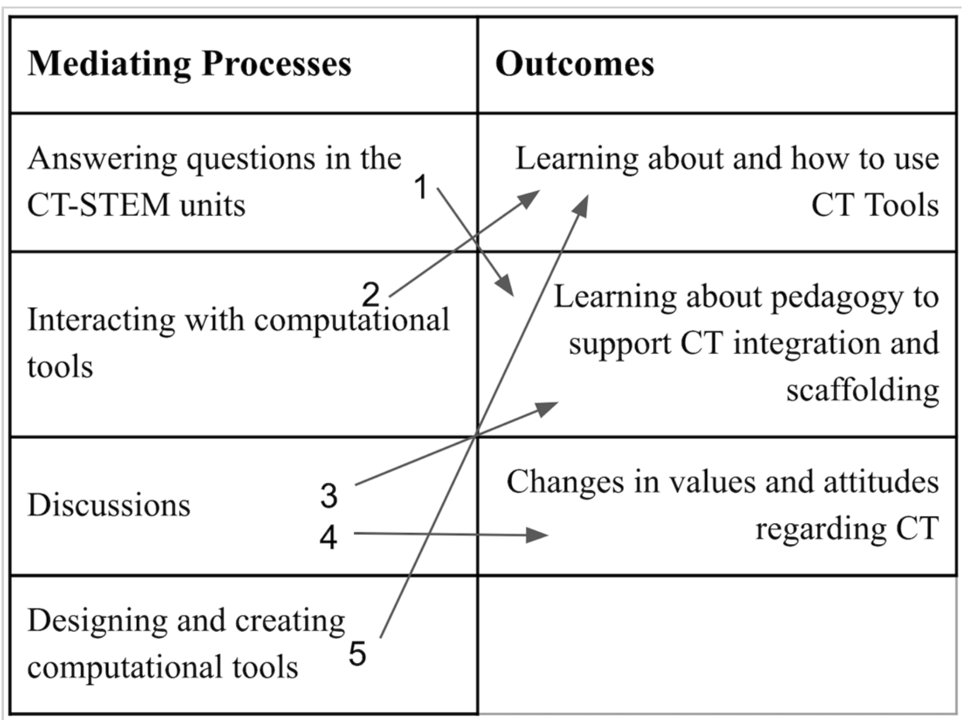


Figure 2. Connections between mediating processes and teacher outcomes.

Table 4. Quotations and examples of interactions connecting mediating processes and teacher outcomes. Arrows are depicted in Figure 1.

| Arrow | Quotation | Explanation |
|---|---|---|
| 1 | Paraphrased:<br>1:52:00 - Tracy:<br>seeing what kids go through. I was behind, but not because I wasn't doing the work. Easy to "get lost" messing around.<br>Also see value of working with a partner (Intro to computational models lesson video) | After engaging in the intro to computational models lesson as a student, Tracy learned about how students engage in computational tools. This is an example of her learning how to support her students in learning with computation. |

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| 2 | Elsie: (19:26)<br>is it intentional that the mice are different sizes?<br>Researcher1: (19:31)<br>Are some of the smaller ones are babies, right? No?<br>Researcher2: (19:33)<br>That's a good observation. And you can, you can test it by changing the values and, okay. Yeah. And if you figure it out, you can share it with the rest of the class.<br>Derick: (19:45)<br>Maybe it's males or females.<br>Researcher2: (19:46)<br>Oh, you figured it out, maybe. Oh, is that what it is? You can test it.<br>Derick: (19:52)<br>Let's find out.<br>(Demonstration lesson video) | As the teachers engaged as learners in Tracy's Hardy Weinberg lesson, they asked questions about the model and experimented to understand the model. This is an example of how interacting with computational tools can lead to learning about that tool. |
| 3 | Christy: (01:23:34)<br>they will have maybe a whole hundred minutes sitting in front of a computer and maybe the next a hundred minute lesson and maybe they're not in front of a computer at all. That doesn't mean that's not CT STEM. Um, and plus it's also really nice to change it up. So like everyone doesn't have to think that, okay, for my entire CT STEM integration, the kids are going to be parked in front of a laptop for a month or two weeks or whatever.<br>(Demonstration lesson discussion video) | During a discussion, Christy shares her views of CT-STEM units and how they don't have to be completely on the computer. This is an example of how a discussion can shape pedagogy related to CT lessons. |
| 4 | Tracy: (57:54)<br>They learned a lot more than they thought they were talking to it. 'Cause there was a lot of complaints. You're going to make me think you want me to write another question, you know, so, but they ended up, I think really learning this concept better than ever. The Hardy Wienberg concept and how it's used. Because before it seemed like just don't random equation that we had the kids memorize that we didn't do anything with and here they got to do something with it.<br>(Demonstration lesson discussion video) | During Tracy's discussion about her natural selection unit implemented last year, she discussed student outcomes with the group. This is an example of how a discussion might result in changes in values and attitudes regarding CT. |

| | | |
|---|---|---|
| 5 | "I updated my second lesson to incorporate CODAP and I feel like I learned a lot of the functionality of CODAP in that process" (Christy, weekly reflection, week 3). | This teacher learned about a computational tool by designing with that tool and integrating it into her unit. |

Table 5. Conjecture Map for the design of the 2020 PD

| **Conjectures** | **Embodiment** | **Mediating Processes** | **Outcomes** |
|---|---|---|---|
| Teacher engagement in workshops as learners followed by explicit reflection leads to learning about CT and changes in perceptions of CT. | Workshops in which teachers engaged as learners. | Answering questions in the CT-STEM units | Learning about and how to use CT Tools |
| | Workshops in which teachers reflected on pedagogy, CT content, science content, and planned their unit design. | Interacting with computational tools | Learning about pedagogy to support CT integration and scaffolding |
| Co-design allows for learning about CT and changes in perceptions of CT. | Feedback from other teachers and STEM experts. | Discussions | Changes in values and attitudes regarding CT |
| | Co-design in which teachers worked with researchers. | Designing and creating computational tools | CT-integrated units |

Table 6. Desired student outcomes for CT-integrated science and math units

| **Desired Student Outcomes** |
|---|
| Students develop computational thinking skills |
| Students learn science and/or math content better than in a normal lesson |
| Students learn/understand how STEM professionals use CT |
| Students learn value of CT as a way to learn and as an important skill-set |
| Students learn/explore how computing can impact scientific thinking and practice |
| Students develop science/CT identities- I am someone who can do science/CT |
| Students feel comfortable with and see struggle as productive struggle |

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| Students do not feel stupid or incapable of doing the kind of work and thinking covered in units |
| Students feel they belong in this kind of learning community |