A Case Study of Teacher Professional Growth Through Co-design and Implementation of Computationally Enriched Biology Units

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Abstract: Teachers in K-12 science classrooms play a key role in helping their students engage in computational thinking (CT) activities that reflect authentic science practices. However, we know less about how to support teachers in integrating CT into their classrooms. This paper presents a case of one science teacher over three years as she participated in a Design Based Implementation Research project focused on integrating CT into science curriculum. We analyze her professional growth as a designer and instructor as she created and implemented three computationally-enriched science units with the support of our research team. Results suggest that she became more confident in her understanding of and ability, leading to greater integration of CT in the science units. Relationships with the research team and co-design experiences mediated this growth. Findings yield implications for how best to support teachers in collaborative curriculum design.

Introduction

With computing becoming ubiquitous in the science, technology, engineering, and mathematics (STEM) fields and society more broadly, researchers have argued that it is crucial to build foundational computational literacy skills in K-12 settings (Wilensky, Brady, & Horn, 2014). One approach in this endeavor is to integrate computational thinking (CT) into core science courses such as biology, chemistry, and physics. Contrary to elective computer science courses offered in high school, the integration of CT into science courses ensures all students engage in computing and build computational literacy, overcoming issues of underrepresentation and self-selection common in computing fields (Wilensky et al., 2014). Research has also demonstrated that the integration of CT into science can not only help increase CT understandings, but also to support deeper science learning (e.g., Blikstein & Wilensky, 2008; Peel, Sadler, & Friedrichsen, 2019).

A number of popular definitions of CT now exist, including perspectives that are closely tied to the domain of computer science (e.g., Wing 2006) as well as perspectives that attempt to understand CT in the context of specific disciplinary practice (e.g., Weintrop et al., 2016). In particular, a taxonomy of CT practices in the context of scientific inquiry proposed four major strands: data practices, modeling and simulation practices, computational problem-solving practices, and systems thinking practices (Weintrop et al., 2016). In this paper, we focus on *modeling and simulation practices* (using, modifying and creating computational models) and *data practices* (collecting, cleaning, visualizing, and analyzing data). Through CT-STEM practices, students learn science content while engaging in authentic STEM practices used in modern science.

Although there is wide support for CT-STEM in K-12 education, it is far from certain that teachers are prepared for such integrations (Cuny, 2012; State of Computer Science Education, 2018). Investigations of teachers' understandings of CT indicate that they hold misunderstandings about CT and are not prepared to incorporate it into classrooms (Sands et al., 2018). Additionally, barriers such as low self-confidence and self-efficacy for teaching CT persist (Aljowaed et al., 2018; Wu et al., 2018). Sands and colleagues (2018) suggest CT should be introduced with explicit attention given to how CT helps students learn disciplinary content.

To address these barriers, our research team focuses on integrating CT and high school science by working with teachers to reimagine classroom practices and learn these new computational practices and tools (Ball & Forzani 2009; Lampert et al. 2013, Windschitl et al., 2012). We view teachers as agents of change towards sustainable curricular reform (Midgley & Wood, 1993). Thus, we focus our investigation on changes to professional growth as teachers engage in professional development and integration of computationally enriched science units. Using a Design Based Implementation Research (DBIR) framework (Fishman et al., 2003), this paper describes an in-depth case study of one teacher's experiences with our team as she learned how to integrate CT and science through multiple co-design sessions and implementations over three years. We investigate her experiences using the following research questions: 1) What, if any, professional growth occurs? 2) What experiences mediated professional growth and changes?

To address these questions, we use the integrated model of professional growth (IMPG; Clarke & Hollingsworth, 2002) to characterize sequences of change in four professional domains: *external domain*, *personal* *domain*, *domain of practice*, and *domain of consequence.* The *external domain* includes interactions outside the teacher's professional world, which is the research team in this case. The *personal domain* consists of changes in teachers' knowledge, beliefs and attitudes, which in this case includes knowledge of CT and comfort with CT and its integration. The *domain of practice* is classroom experimentation, or changes in practice through implementing the CT integrated unit. The *domain of consequence* consists of changes in teachers' perception of salient outcomes, such as in student learning and development. Change in one domain can lead to change in another through enactment or reflection. Enactment (depicted as solid arrows in Figure 1) is the translation of a change into an action or taking action. For example, our focal teacher enacted new CT integrated units from the research team, thus linking the *external domain* and the *domain of practice* (Arrow 2). Reflection (depicted as dashed arrows) is the change through active reflection on the change and its impacts. The IMPG characterizes change sequences as our focal teacher designed and implemented CT integrated units.

Methods

Our focal teacher, Tracey (a pseudonym), worked with our team in a design-based research project to implement and design CT integrated curricula for three years. In year one, she was given a CT integrated biology unit designed by the research team. She provided feedback on the unit and implemented it in her classrooms with support from the research team. In year two, Tracey provided direction as researchers designed a new CT integrated unit. She chose the biology content, provided her lesson plans, and gave feedback as lessons were designed. She then implemented the new unit. In year three, Tracey worked with a member of the research team to co-design a new unit during a Computational Thinking Summer Institute (CTSI). Tracey and the researcher (Author 2) worked together to design lessons and computational tools, which she implemented in her classroom.

Through this multi-year process, we collected data to characterize Tracey's experiences. The data sources include interviews after each year's implementation and various data collected during the summer co-design workshop: weekly reflections, session recordings, a post-workshop interview, and pre- and post-workshop surveys. Additionally, we reviewed the curricular units and classroom video of implementations to support the analysis. We used a case-study method (Yin, 2004) to analyze Tracey's *personal domain* regarding her knowledge, beliefs, and attitudes and how that impacted her involvement in design (*external domain*), implementation (*domain of practice*), and views of student outcomes (*domain of consequence*). Three coders analyzed data sources for the four domains. Then, a secondary round of coding was used to identify connections between the domains and develop change sequences in professional growth for each year. The claims and codes were triangulated where possible with multiple data sources. It is important to note that interactions between the four domains are complex and many interactions happen implicitly. Therefore, the professional growth model diagrams constructed in this case study only depict connections explicitly supported by the data.

Results

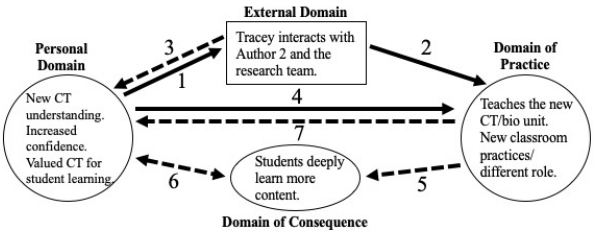

Figure 1. Salient connections in Tracey's professional growth.

Year one

External domain

In year one, the research team designed the CT integrated biology unit (described below) and walked through the unit with Tracey (Figure 1. *External Domain*). She was asked to provide feedback and make changes to improve the models and embedded questions. However, she only suggested some corrections of typos. Tracey then implemented the units designed by the team without providing design input: "...the first year, before every lesson, [Author 2] would come the day before or a few days before, and we would go over the entire lesson what the kids were supposed to learn from it, how they were supposed to set it up" (CTSI Session).

Domain of practice: Unit and pedagogy

From Ecosystems to Speciation is a two-week unit that focuses on prey-predator ecosystems, competition between individuals, mechanisms of microevolution (genetic drift and natural selection), and speciation. Activities are available online at: https://ct-stem.northwestern.edu/curriculum/preview/199/. Students explored six models designed using NetLogo, an agent-based computational modeling environment (Wilensky, 1999), and investigated real world data of Galapagos Finches using Common Online Data Analysis Platform (CODAP; https://codap.concord.org/). The learning objectives primarily focus on disciplinary understanding of ecological relationships and evolutionary changes in populations. Throughout this unit, students were asked to use the model to make observations and inferences regarding disciplinary ideas, engaging in the CT-STEM practice: Using a computational model to understand concepts.

When Tracey implemented the unit (Figure 1, Arrow 2), the *external domain* influenced the *domain of practice.* When asked about her pedagogy during implementation, she said each student progressed at their own pace, so it was hard for her to have whole class discussions. She also said her role switched from leading the class to letting students take ownership of their own learning through the unit: "I always taught, where like I am in control of everything they learn...this is the kids learning it at their own pace and discovering it on their own. And I have to just step back and just kind of be I don't know, not even a facilitator just I know, they're just doing it on their own" (Year 1 interview). Further, Tracey said because she was not fully aware of what the students were doing, she was not sure how to facilitate their learning, resulting in a less active teaching role.

Domain of consequence

After implementation, Tracey reflected on student outcomes, thus connecting the *domain of practice* and *the domain of consequence* (Figure 1, Arrow 5). Tracey was surprised by the engagement of some of her students who were typically not engaged: "there were the kids that were sometimes not engaged in other activities that absolutely loved running these models and coming up the questions and running them. It was really surprising to me" (CTSI Session). She also reflected on student learning outcomes, recognizing the value in teaching her content with computation: "I think this is the first time that kids have a real understanding that evolution can happen because of random forces, and because of natural selection...I think this is the first time it's come through in my curriculum…what a good way to teach this concept." (Year 1 interview). This reflection placed value in CT, thus connecting the *domain of consequence* and her *personal domain* (Figure 1, Arrow 6).

Personal domain: Confidence and CT knowledge

Tracey began her work with our team with little confidence in her understanding of CT and her abilities related to CT. "I thought it was going to be more of the actual going into the code… I was a little intimidated by that. I don't know how to code. Don't make me code" (Year 1 interview). Her discomfort may have mediated her interactions in the *domain of practice* since she was intimidation by computing. Tracey also indicated a lack of confidence in technology and her reliance on the research team for support. "I'm not a good tech person. I asked 1,000 questions, and it has to be repeated to me over and over and over before I get it" (Year 1 interview). Tracey's confidence was low in her first implementation, which could be due to superficial CT understanding.

Prior to working with our team and implementing, Tracey understood CT as coding. "I thought it was going to be more of the actual going into the code… So I thought it was going to be more of that..." (Year 1 interview). However, after implementing the unit, she had a more nuanced CT understanding including the use of models to understand a science phenomenon: "to see what happens if you change parameters [in a model]. And it's instant, that you get the information like right away, predicting what would happen in an actual ecosystem. So, using computer models to also teach the concepts." (Year 1 interview). This change in CT understanding reflectively links the *domain of practice* and her *personal domain* (Figure 1, Arrow 7).

Year two

External domain

In year two, Tracey's role in designing a new unit shifted. Tracey and the second author had weekly design meetings where she expressed a desire to build a unit about natural selection. She shared materials from her class and explained an activity she normally used to teach this content. "We started from the activities from [last] year working on the ones that were already made… he already asked me, so what do you do? What are the activities that you already do? … and then [he] talked about, well how can we turn these into the computational? (CTSI Session). Based on her input and materials, Author 2 designed a computational model. Next, Author 2 discussed curricular activities with Tracey and then designed the unit. Tracey provided feedback throughout the design process. Her involvement in the design indicates a connection between her *personal domain* and the *external domain* because she was using her knowledge to inform the new unit (Figure1, Arrow 1).

Domain of practice: Unit and pedagogy

Evolution of Populations to Speciation is a two-week unit that focuses on predator-prey dynamics, competition among individuals, and natural selection. Activities are available online via: https://ct-stem.northwestern.edu/curriculum/preview/961/. Typically, on each page, students engage with a description of a computational model, suggestions for exploration, and two to five embedded assessment questions. Most of the questions were open-ended and prompted students to engage in explorations of the model by changing parameters, designing investigations, and making observations. The unit incorporates a NetLogo model about natural selection and adaptation in populations of rock pocket mice in the desert of New Mexico. The lessons engage students in science inquiry and CT practices such as asking questions, stating an answer in the form of a hypothesis, designing and conducting an experiment, collecting data, analyzing data, and arguing with evidence in data to support a claim.

In year two, Tracey implemented the new CT-integrated natural selection unit, connecting the e*xternal domain* and *domain of practice* (Figure 1, Arrow 2). When reflecting on her role during implementation, she saw herself as "more a facilitator. I could go around and ask questions to the kids more so to check their understanding. Actually even to get them to probe deeper into what was happening… I wasn't feeding them the information, but I did some guiding in some cases to let them see the information" (Year 2 interview). Tracey indicated she made changes to lessons as she was implementing to support student learning of both CT and science. For example, she added a discussion of an article about a scientist using computational models to conduct an ecological experiment (Year 2 interview). She also asked students to share their computational approaches: "I would sometimes interrupt and have discussion with the kids about what they were doing" (Year 2 interview). In addition to the unit, Tracey implemented a computational model lesson on her own, suggesting a change in practice influenced by Tracey's knowledge of computational modeling: "...when we were doing ecology, I found a little computational model of my own and did it all by myself with the kids without anyone else around" (CTSI Session). This enactment (*domain of practice*) was brought about by Tracey's *personal domain* (Figure 1, Arrow 4).

Domain of consequence

After implementation, Tracy made a reflective connection between the *domain of practice* and the *domain of consequence* (Figure 1, Arrow 5). She said students learned more from the computationally enriched unit, compared to traditional lectures and prior years' natural selection units: "...their test scores were higher in this class… And now if I'm comparing it to the test they just took the other day, which is a more traditional teaching experience, you know, it was lecture and notes and I think it was even an easier test. The class average was only an 85%" (Year 2 interview). Tracey mentioned that although the students didn't enjoy this unit because it pushed them to figure things out on their own, they had a more in depth understanding of the content. "They learned a lot more than they thought they would because there was a lot of thinking: "You want me to think? You want me to write another question?"...they ended up really learning this concept better than ever." (CTSI Session). Tracey has not only identified changes in student outcomes, but expressed her value in those outcomes by incorporating another modeling lesson on her own. These changes connect Tracey's *personal domain* and the *domain of consequence* (Figure 1, Arrow 6), which led to an enactment in the *domain of practice* (Figure 1, Arrow 4).

Personal domain: Confidence and CT knowledge

After implementing, Tracey reflected on her second implementation and indicated she was more confident: "I was much more confident this year than last year… I feel like I could even go do it myself without you here I can assign something that's already been made to them." (Year 2 interview). Tracey indicated her confidence stemmed from implementing a unit with our team once before, connecting her *personal domain* to both the *external domain* (Figure 1, Arrow 3) and the *domain of practice* (Figure 1, Arrow 7). This confidence is further displayed with the additional modeling activity she taught on her own. She was so confident in her implementation of this addition, she scheduled it on a day she was being observed. "It was an evaluation year for me. So I was bold enough to actually choose that activity when [an administrator] came in" (CTSI Session).

Although she was more confident in implementing a CT integrated unit, Tracey was still uncomfortable with coding and computing. During this implementation, she asked students to share their computational approaches with the class. While this shows a change in pedagogy, she made this change because she was not confident in her own ability. "I felt that that person was more comfortable using the technology than even I was" (Year 2 interview). Additionally, when discussing the next co-design opportunity, she was apprehensive about learning how to build computational models: "You'd have to be really patient. Very slow… Should we try to get [another teacher] to come with me?... she'll know the code faster than me and then if I have to rely on her or ask her questions, she's a resource here." (Year 2 interview). Even after increased comfort from two years of implementing and one year of helping design the curriculum, Tracey was still not comfortable with coding.

In year two, Tracey's CT knowledge constituted a more sophisticated definition with data practices. Tracey described how her students engaged in CT practices: students were "modeling situations that they couldn't actually do in real life because it would take generations for them to go out into a field and count all the mice" (Year 2 interview). Further, students engaged in data practices: "[students] saw how they could very easily sort through male or female, beak size, weight, like just thousands and thousands of data points...like if they were scientists, they would use those tools to analyze data that they had collected." (Year 2 interview). This change in Tracey's CT knowledge links to her implementation and experience with our team, thus connecting the *personal domain* to the *external domain* and the *domain of practice* (Figure 1, Arrows 3 and 7).

Year three

External domain

In year three Tracey participated in a four-week summer institute. In the first week, teachers learned about CT practices and computational tools, such as NetLogo, NetTango (a visual programming interface for NetLogo; Horn & Wilensky, 2011), and CODAP. In the remaining three weeks, Tracey collaboratively designed a new biology unit with the second author. Instead of providing ideas and feedback like in prior years, Tracey helped design the new unit herself. Tracey helped develop new NetLogo models, NetTango models, and data collection with CODAP. She also designed the questions and learning activities with Author 2. Her role in the design provided an enactment connection between her *personal domain* and the *external domain* (Figure 1, Arrow 1).

Domain of practice: Unit and pedagogy

Tracey and Author 2 co-designed the unit, Experimental Design and Computational Thinking, a series of computationally enriched lessons about experimental design and animal behavior. Tracey typically taught an experimental design unit by asking students to conduct experiments with real *Armadillidium vulgares*, or roly-polies which was incorporated into this unit. Tracey's students engaged in the computational activities in the following sequence. They used a NetLogo computational model to perform experiments and analyze data, which involved automated data collection using a then CODAP computational tool. The students modified an existing NetLogo model and finally, constructed a computational model of roly-poly behavior using NetTango. The final model investigated the environmental preference behavior of rolly-pollies. The model consists of two interconnected chambers containing rolly-pollies. A user can set pre-coded conditions in each chamber, for example, moist or dry. Users can easily add more conditions of their choice and can set which conditions rolly-pollies prefer. If a rolly-polly is on a location that has its preferred condition, the probability of its movement is lower than when it is on a non-preferred location. This simple probabilistic behavior results in an emergent pattern of distribution of bugs reflecting what is observed in the real-world experiment.

When Tracey implemented her new co-designed CT and biology unit, she once again saw her role as a facilitator of learning. In this implementation, however, she clearly connects her role to the design of the unit, saying the unit was designed to engage students in sense-making on their own. "[Students] were learning it on their own. They only called me when they needed me. I would just go around and be excited if they did something really cool... It's because we spend so much time designing them and writing the little videos and that they didn't need me" (Year 3 Interview). This reflection connects the *external domain* and the *domain of practice* (Figure 1, Arrow 2). In prior implementations, the research team helped students debug models, but this year, Tracey engaged the class in debugging code herself. She walked through the steps to find the problem and asked prompting questions to fix the code. "I saw them thinking in every aspect, looking at the code, try to find out why it wasn't working, why the bug was and it was blue and how to change it" (Year 3 Interview). This change in pedagogy was enacted due to her experiences during the summer co-design institute. She translated her debugging knowledge into her instructional practice, thus connecting the *external domain* to Tracey's *personal domain* (Figure 1, Arrow 3) to the *domain of practice* (Figure 1, Arrow 4).

Domain of consequence

After teaching, Tracey reflected on student learning gains and indicated students learned science content better than in prior years. "[Students] were able to do well on the assessment only from what they did by completing this unit. So they, they not only learned the computation how, how to use a computational model, they learn the content I needed for their AP test" (Year 3 Interview). While the attention given to science learning is not different from prior years, in this implementation, she also said students learned about how real scientists do science with computing: "They learn absolutely way more about experimental design and how a scientists would conduct the lab and, and how they would actually collect data and analyze that data" (Year 3 Interview). In reflecting on the implementation and identifying new student outcomes, Tracey has connected the *domain of practice* to the *domain of consequence* (Figure 1, Arrow 5). In addition, Tracey valued CT integration and the outcomes it provided her students. When asked if she thought the CT integration was a useful approach to teaching science compared to traditional instruction, Tracey said, “Yeah, I would definitely not go back to - I like this a lot” (Year 3 Interview). This reflectively connects *domain of consequence* and her *personal domain* (Figure 1, Arrow 6).

Personal domain: Confidence and CT knowledge

In the weekly reflections of the co-design workshop, she described gaining confidence in CT in Week 3: “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 a little trouble-shooting and be less reliant on the team that observed my classes.” Further, she expressed surprise in her use of code and integration of a new CT tool into her lessons in Week 4: “I have come a long way since the first time I worked with [the team] 3 years ago. I didn't think I would ever dig into the code or use NetTango in a lesson.” In addition, the pre/post CTSI survey showed that Tracey’s confidence increased in her ability to identify and define computational data and computational modeling practices. She felt more confident in her ability to engage students in CT data and modeling practices, adapt lessons to integrate these CT practices, find resources to support CT integration, and help colleagues integrate data and modeling practices. The largest shift in confidence was in her “ability to create an original science lessons that includes computational data/modeling practices” and “answer student questions regarding computational data/modeling activities.” In both cases, she “neither agree nor disagree” in her pre-survey and “strongly agree” or “agree” in the post-survey.

When talking about helping her students debug, Tracey said the summer co-design experiences helped her feel confident: “I think because I worked with you all summer, I wasn't as nervous” (Year 3 Interview). After three years of implementation and working with our team, Tracey said she felt confident enough to implement CT integrated units on her own. The change in confidence due to her co-design and implementation experiences links her *personal domain* with the *external domain* (Figure 1, Arrow 3) and *domain of practice* (Arrow 7).

Regarding CT knowledge, Tracey described CT as “using computer models to explain phenomenon, to test variables, predict outcomes, analyze data” (CTSI Pre-survey) prior to the co-design summer institute in year three. After the institute and co-design, she added the connection to authentic science practices to her definition. CT is “[u]sing and designing computer models to test variables, design experiment[s], make predictions. Also, using computation tools as a way to collect and analyze data the way a scientist would actually do it” (CTSI Post-Survey). Additionally, Tracey said she learned about computational tools and coding through the institute: “I knew nothing about coding and the little patches and now you have to ask things to move into these. I had no idea...I can not code anything. Maybe a tiny little change I can make, but I at least see now what goes into it. And I think I'll be better at explaining things to the kids” (CTSI Post-interview). Tracey’s changes in her CT understanding and coding knowledge connects the *external domain* and her *personal domain* (Figure 1, Arrow 3). Additionally, her knowledge of CT translated into the classroom when she debugged with her students, thus connecting her *personal domain* to the *domain of practice* (Figure 1, Arrow 4).

What mediated the professional growth and changes?

After three years of working with our team in varying capacities ranging from training to prolonged co-design, Tracey grew professionally, as demonstrated by changes in all four domains and their interactions. Several interactions and experiences mediated Tracey’s professional growth, including increased involvement in the co-design process, personal relationships with Author 2, support from the research team, and implementation experience.

Tracey’s increased involvement with the *external domain* during the co-design process mediated changes in her *personal domain* and *domain of practice*. In the first year, Tracey used the team’s unit. In year two, she provided direction for the design of CT integrated tools with her chosen content. Finally, Tracey was involved in designing and building CT integrated tools and the curriculum. Tracey indicated co-design (*external domain*) was an important aspect in building her comfort, confidence, and CT understanding: “Co-designing it was critical. Not only did you make it fit my curriculum, but I also knew what was coming…co-working builds trust. I could ask questions, I could say ahead of time, I don't understand this. Can you add a question about this? Can we have this?” (Year 2 interview). That is, in her *personal domain*, Tracey gained confidence with CT and its integration and her CT understanding became more nuanced and detailed. The curriculum (*domain of practice*) shifted throughout Tracey’s three years in terms of how CT was being integrated. In year one CT was not central. Although every lesson had a computational tool, the focus was science learning. In year two, the lessons engaged students in open-ended activities with computational tools. The computational tools were specifically designed for her content, making them more integrated with the science than year one. In year three, the CT integration continued to increase. Students engaged in using computational tools, modifying the code of computational tools, and creating a new computational model. With this shift in CT integration came an increased focus on learning CT skills and developing CT understanding along with the science content. Tracey’s pedagogy in the *domain of practice* also changed as the units transitioned from using computational tools in year one, to open-ended investigations with computational tools in year two, to debugging and coding in the classroom in year three. Tracey’s classroom role shifted from being in the background in year one, to making changes in year two (discussions, asking students to share), to being confident in year three such that she debugged on her own.

Tracey's personal relationship with Author 2 (*external domain*), through working with him over the three years, mediated changes in her *personal domain*. Tracey developed trust in Author 2 and made her comfortable with being uncomfortable throughout the design process: "because I worked with [Author 2] in the past and because I did that summer work with you, I have a lot of trust in you guys...I'm very comfortable taking that risk with [Author 2] because you will hold my hand through it if necessary" (Year 2 interview).

Tracey also valued the continued support from the team (*external domain*) during her implementations (*domain of practice*) and the summer co-design institute. These interactions mediated changes in her *personal domain* and *domain of practice*. Although she was uncomfortable with computing herself, the support from the research team made her feel comfortable in implementing new computationally enriched units. "I'm the one nervous about using any kind of computational tool or model... I was glad that you were there." (CTSI Session). The classroom support was important to Tracey, especially in years one and two, because she was uncomfortable with computing and she did not feel like she could answer students' questions. She needed to see how the research team dealt with questions and issues in order to effectively do so herself. The support during implementations was also important to Tracey because it helped form a classroom culture of comfort with asking questions and figuring things out: "I think because I was so open about asking for help that the kids were never shy…the kids never felt like they were going to ask a dumb question because they saw me ask so many of them." (CTSI Session). The presence of the research team was a source of comfort and learning for Tracey and her students.

Tracey's implementation experience (*domain of practice*) over the years impacted her *personal domain* and the *domain of consequence*. Tracey mentioned her increased confidence stemmed from multiple experiences teaching the units. She said the repetition of implementing the computational models was important. For example, she was more comfortable in year two because she had taught it and seen the computational model before. Multiple implementations also may have allowed Tracey to identify and value changes in student outcomes, in the *domain of consequence*, throughout the three years. In year one, Tracey saw the value in teaching the content with computational tools, but struggled to identify specific learning of the science content since formative assessments were not built into the unit. In year two, Tracey identified greater content learning gains than in prior years and compared to other non-computing units (Year 2 interview). In year three, she noted the same increased science content learning, but she also noticed and valued student learning related to CT and its important role in authentic science.

Discussion

There is little known about how teachers implement CT in science, and even less is known about how to support teachers in designing and implementing CT integrated curriculum (Sands, Yadav, & Good, 2018). Although this work focused on one teacher's experience, it contributes knowledge on how to help teachers design and implement computing enriched curriculum that integrates CT and science.

First, developing *trust and relationships* between teachers and researchers (*external domain*) can help teachers feel comfortable with new integrations. This is especially important if teachers are intimidated by computing, as seen with Tracey. Second, *classroom support during implementations* may help teachers feel more confident and willing to implement new technology in their classrooms (*domain of practice*). It is evident in this case that Tracey would not have implemented CT integrated units without continued support from the research team. Third, the *co-design process* can foster professional growth and improve outcomes in the classroom. For Tracey, the co-design process increased her comfort and CT knowledge while positively impacting her teaching practice and CT integrated curriculum. Co-design supports teacher understanding of the technology being used and thus may result in more sophisticated curricula since teachers are designing with and learning from experts (Voogt et al., 2016). In Tracey's case, there is clear growth in her understanding of CT (*personal domain*) as well as in her units with the increasingly sophisticated use of computational tools. In early years, the units engaged students in using computational tools, but in year three, the students use computational tools, modify the code running the computational tool, and even create their own computational tool with NetTango. Finally, *scaffolding teachers' participation in design* may help them become sustainable CT implementers. Tracey's professional growth increased with each year of working with the research team as she became more central as a designer of her curriculum. After year three, she was confident in her ability to implement computationally enriched units on her own. For teachers without computing experience, becoming confident and competent in teaching and designing CT integrated curriculum may require a long-term commitment to scaffolded design experiences.

Teachers face many challenges and barriers when integrating CT and science, such as inadequate computer science training and a lack of support through professional development (Aljowaed at al., 2018; Yadav et al., 2016). Our findings suggest relationships with researchers and co-design can support teachers in this integration. While this case is only one teacher, Tracey displayed many of the common discomforts and barriers to implementation, suggesting this work can inform the support of a broad range of teachers. We posit that teachers more comfortable with computing will benefit from co-design, but it may not require as much scaffolding or time. However, this relationship becomes challenging for up-scaling CT integration when close personal relationships cannot be developed. Future investigations in scaling up implementations and integrations are needed.

References

2018 State of Computer Science Education. (2018). Retrieved from https://advocacy.code.org/.

Aljowaed, M., & Alebaikan, R. A. (2018). Training needs for computer teachers to use and teach computational thinking skills. *International Journal for Research in Education, 42*(3), 237-284.

Ball, D., & Forzani, F. (2009). The work of teaching and the challenge for teacher education. *Journal of teacher education, 60*(5), 497-511.

Blikstein, P., & Wilensky, U. (2008). Implementing multi-agent modeling in the classroom: Lessons from empirical studies in undergraduate engineering education. In *M. Jacobson (Chair) & R. Noss, Complex systems & learning: Empirical research, issues & "seeing" scientific knowledge with new eyes." Proceedings of the International Conference of the Learning Sciences (ICLS)* (Vol. 3, pp. 266-267).

Clarke, D., & Hollingsworth, H. (2002). Elaborating a model of teacher professional growth. *Teaching and teacher education, 18*(8), 947-967.

Cuny, J. (2012). Transforming high school computing: A call to action. ACM Inroads, 3(2), 32-36.

Fishman, B. J., Marx, R. W., Best, S., & Tal, R. T. (2003). Linking teacher and student learning to improve professional development in systemic reform. *Teaching and teacher education*, *19*(6), 643-658.

Lampert, M., Franke, M. L., Kazemi, E., Ghousseini, H., Turrou, A. C., Beasley, H., ... & Crowe, K. (2013). Keeping it complex: Using rehearsals to support novice teacher learning of ambitious teaching. *Journal of Teacher Education, 64*(3), 226-243.

Midgley, C., & Wood, S. (1993). Beyond site-based management: Empowering teachers to reform schools. *The Phi Delta Kappan,75*(3), 245-252.

Peel, A., Sadler, T. D., & Friedrichsen, P. (2019). Learning natural selection through computational thinking: Unplugged design of algorithmic explanations. *Journal of Research in Science Teaching*, *56*(7), 983-1007.

Sands, P., Yadav, A., & Good, J. (2018). Computational thinking in K-12: In-service teacher perceptions of computational thinking. In Computational Thinking in the STEM Disciplines (pp. 151-164). Springer, Cham.

Voogt, J.M., Pieters, J. & Handelzalts, A. "Teacher collaboration in curriculum design teams: Effects, mechanisms, and conditions." *Educational Research and Evaluation* 22, no. 3-4 (2016): 121-140.

Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., & Wilensky, U. (2016). Defining computational thinking for mathematics and science classrooms. *Journal of Science Education and Technology, 25*(1), 127-147.

Wilensky, U. (1999). NetLogo. Evanston, IL: Center for connected learning and computer-based modeling, Northwestern University.

Wilensky, U., Brady, C. E., & Horn, M. S. (2014). Fostering computational literacy in science classrooms. *Commun. ACM*, *57*(8), 24-28.

Wilensky, U. & Horn, M. (2011). NetTango. Software, Evanston, IL.

Windschitl, M., Thompson, J., Braaten, M., & Stroupe, D. (2012). Proposing a core set of instructional practices and tools for teachers of science. Science education, 96(5), 878-903.

Wing, J. M. (2006). Computational thinking. *Communications of the ACM*, 49(3), 33-35.

Wu, L., Looi, C.-K., Liu, L., & How, M.-L. (2018). Understanding and Developing In-Service Teachers' Perceptions towards Teaching in Computational Thinking: Two Studies. *Proceedings of the 26th International Conference on Computers in Education.*

Yadav, A., Gretter, S., Hambrusch, S., & Sands, P. (2016). Expanding computer science education in schools: understanding teacher experiences and challenges. *Computer Science Education*, *26*(4), 235–254.

Yin, R. K. (2004). *The case study anthology*. Sage.

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