

Empowering Science Teachers through Computational Thinking

Margaret Cozzens, Tamra Carpenter

The Center for Discrete Mathematics and Theoretical Computer Science (DIMACS), Rutgers University, Piscataway, USA
Email: mcozzens@dimacs.rutgers.edu, tcar@dimacs.rutgers.edu

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Abstract

Teachers are often positioned as targets or agents of reform in professional development (Sykes & Wilson, 2016). This paper discusses empowering high school teachers through professional development opportunities around computational thinking where the goal of integrating computational thinking (CT) into existing practice shifts attention away from a particular instructional approach to providing teachers with the opportunity to fold adapted CT materials into their existing practice, thus teachers become agents. From the participants' perspective, DIMACS Computational Thinking Professional Development for Mathematics and Science Teachers (CTPD) achieved its primary goals of expanding teachers' abilities to think computationally, especially in terms of decomposing and testing out various solutions; and they gained familiarity with a wide range of activities and units that they could adapt for use in their classrooms (Wilson et al., 2023). A number of examples of science teachers, who have invented their own additions of CT to their courses are provided, including one from a third grade teacher.

Keywords

Science Teaching, Computational Thinking, Professional Development, Creative Thinking

1. Introduction

All K-12 Students need to learn computational thinking (CT) and analytical skills. This has been a common call for nearly twenty years across the United States and in countries or regions including the United Kingdom (The Royal Society, 2012), Germany, Spain, Australia (Bower et al., 2017), Denmark (Tuhkala et al., 2019), Taiwan Region (China) (Hou et al., 2020), and Malaysia (Ung et al., 2022), to give just a few examples. Each nation describes this need based on 21st century skills

needed for success in virtually every discipline, though the definitions of computational thinking often vary.

Wing (2006, 2008) described CT as the skill set one acquires when learning computer science and offered abstraction, decomposition, recursion and other examples of such skills. A report of the National Research Council built on Wing's foundation, noting that "computational thinking might include reformulation of difficult problems by reduction and transformations; approximate solutions; parallel processing; checking and model checking as generalizations of dimensional analysis; error prevention, testing, recovery and correction; damage containment; simulation; heuristic reasoning, planning, learning, and scheduling in the presence of uncertainty; search strategies, analysis of the computational complexity of algorithms and processes; and balancing computational costs against other design criteria (NRC, 2010: p. 3)". The International Society for Teaching Education (ISTE) and Computer Science Teachers Association (CSTA) soon followed with an operational definition of computational thinking developed with K-12 teachers in mind (see also (Barr et al., 2011)). The ISTE/CSTA definition is quoted below and is largely how we define CT in this paper and in the curriculum and professional development described herein.

ISTE/CSTA OPERATIONAL DEFINITION OF CT

Computational thinking (CT) is a problem-solving process that includes (but is not limited to) the following characteristics:

- Formulating problems in a way that enables us to use a computer and other tools to help solve them.
- Logically organizing and analyzing data
- Representing data through abstractions such as models and simulations
- Automating solutions through algorithmic thinking (a series of ordered steps)
- Identifying, analyzing, and implementing possible solutions with the goal of achieving the most
- efficient and effective combination of steps and resources
- Generalizing and transferring this problem solving process to a wide variety of problems

These skills are supported and enhanced by a number of dispositions or attitudes that are essential dimensions of CT. These dispositions or attitudes include:

- Confidence in dealing with complexity
- Persistence in working with difficult problems
- Tolerance for ambiguity
- The ability to deal with open ended problems
- The ability to communicate and work with others to achieve a common goal or solution

(International Society for Teaching Education (ISTE) and Computer Science Teachers Association (CSTA), 2011)

Our project (CTPD) was informed by these foundational works, but alternative definitions of CT abound, and the range of what CT encompasses or is encompassed

is extremely broad—including computer science, computational literacy, computer technology, mathematical thinking, or programming. This seemingly ever-expanding list of aspects of computational thinking, combined with confusion over the distinctions between computer science, computational literacy (di Sessa, 2018), using computer technology, and computational thinking continues to plague the field. Complicating things further is confusion about whether computational thinking ought to be taught across the curriculum and grade levels or whether it should be limited to specialized computer science or mathematics classes (Tannert et al., 2021; Furt et al., 2023). By viewing CT as part of computer science we run the risk of understating its importance in other disciplines, especially science disciplines.

No matter the definition of CT, whether it includes programming or not, or at what grade level it is taught, the onus for bringing CT to students is on teachers. With computational thinking among the eight science and engineering practices included in the Next Generation Science Standards (NGSS Lead States, 2013; NRC, 2011, 2012) being adopted across the U.S.; this is especially true of science teachers in science classrooms. Despite the call for inclusion of CT in science classrooms, many teachers have little experience with or knowledge of CT content. Thus, with the calls for instruction in CT comes the need for professional development for teachers. In this paper, we describe the CTPD project that designed and tested a professional development (PD) course to enable high school teachers from a variety of science and mathematics disciplines to bring CT into their classrooms. By illustrating CT concepts within the context of problems such as DNA sequencing, medical tomography, and weather simulation, teachers across the country have learned computational thinking content and been empowered to adapt what they learned for their own classes, especially science classes. In section two of this paper, we describe the computational thinking curriculum and modules, and the design of the computational thinking professional development. Examples of teacher inventions of CT materials that they successfully added to their own science classes are given in the third section. Finally, there are some general conclusions and indications of how to get the materials described earlier.

2. Computational Thinking Professional Development in the CTPD Project

The CTPD project began in late 2018 and consisted of three primary areas of activity: 1) Design and development of materials for a PD course in computational thinking; 2) Delivering materials to teachers around the country through in-person workshops followed by an on-line course; 3) Research testing the efficacy of the professional development delivered. The CTPD professional development course was delivered largely online, but online use was preceded by short in-person workshops for eight cohorts of 20 - 25 teachers in a local geographic area. The workshops were conceived of as a critical bridge for introducing teachers to CT, the online platform, and to each other. After the workshop, the professional

development continued with 4- or 8-week online programs, creating a hybrid form of PD and a community of teachers learning CT. When the COVID-19 pandemic struck in 2020, the pre-course workshop was modified from being held in person to being held synchronously online.

2.1. Computational Thinking Curriculum & Course Design

The online course was based on existing classroom materials developed and tested in a previous project led by the first author. That project, Value of Computational Thinking across Grade Levels 9 - 12 (VCTAL), developed and extensively tested a set of twelve modules that introduced CT concepts in the context of a variety of real-life applications. The modules are self-contained, student-centered, and activity-driven, each covering five or more 40-minute classes. Each VCTAL module includes a section on “How to Use the Module” that discusses grade levels appropriate for the material, student preparation, format of module, references, supplementary materials, and relevant standards. The emphasis within each module is on setting up models and understanding them. All of the VCTAL modules are available for download from the Consortium for Mathematics and Its Applications (COMAP, 2024b).

The CTPD course is made up of an introductory unit that introduces the course goals, the online platform (Canvas), and basic concepts in computational thinking, followed by ten “regular” units. Each regular unit follows a similar pedagogical sequence from initial context and problem to computational perspective to concept generalization and transfer. This pedagogical sequence parallels what teachers do in their classrooms, and includes an initial scenario posing a driving question or problem, exploration of the CT context, formalization of core CT concepts, construction of an approach to solve the driving question, introduction of related applications, and abstraction and transfer of CT concepts to these new contexts. The use of videos, activities, other media (e.g. applets), and frequent discussions frame the units for easy adaptation to classroom use. Nine of the ten regular units are based on VCTAL modules, which provide more extensive background and a ready source of teaching materials. The tenth PD unit, *Weather Generators*, is based on a module from a different project that was adapted to include more explicit examples of computational thinking in simulating weather. It is also available for download from COMAP (COMAP, 2024a).

Each online unit adapted portions of the module on which it was based to make it appropriate for self-directed online professional development. Some units, such as *Weather Generators*, added new content to enhance the connection with CT and/or high school science curricula. Many units also added new online resources such as websites, videos, applets, and spreadsheets that teachers can adapt for classroom use. Some of those resources were already available, while others were designed as part of the project with teacher professional development in mind. The units included in the course are:

- **Unit 0: What is Computational Thinking?:** This unit introduces basic

vocabulary and concepts that make up computational thinking, including the notion of an algorithm; provides links to online CT resources; and introduces the online platform. It is taught during the orientation workshop.

- **Unit 1: Privacy:** The Privacy unit is driven by case studies that touch on everyday life. Sample case studies show how information revealed in Netflix ratings, loyalty card purchases, and even Web searches can inadvertently compromise other private information. The module invites the PD teachers to develop their CT skills by questioning how privacy issues are incorporated in the modern data-rich environment and by appreciating the logic and algorithms behind the design of online and offline data sharing methods.
- **Unit 2: Electric Car:** This unit explores the cost of an electric car relative to a gas-powered car, both in terms of financial cost and environmental cost through release of greenhouse gasses. The unit introduces spreadsheets as a means to organize and analyze data to enhance decision-making and invokes other fundamental CT skills such as abstraction and decomposition.
- **Unit 3: Network Capacity:** This unit illustrates how “networks” can be used to model a variety of real-life systems, ranging from familial relationships to traffic congestion. In addition to demonstrating how to abstract from real systems to network models, the unit introduces the notion of simulation to capture uncertainties related to flows in networks and the potential for congestion. Networks can be used to model a variety of concepts in biology and chemistry.
- **Unit 4: Heart Transplant:** This unit engages the PD teachers in organizing and analyzing data in order to determine which patients awaiting a heart transplant should receive the available hearts. Participants are then challenged to “algorithmize” their thought process by creating a ranking system that could be used to prioritize new patients or assign new hearts as they become available. This unit ties less directly with curriculum standards, but many of the teachers found ways to adapt the ideas to their classrooms.
- **Unit 5: DNA Sequencing and Sorting:** In this unit the PD teachers use algorithmic thinking to identify where short DNA sequences fit in a reference genome to illustrate the mapping process used in genome sequencing and the types of genomic variations that can be discovered as a result of this mapping. Through these activities, participants appreciate the need to develop efficient procedures for genome sequencing.
- **Unit 6: Recurrences:** This unit demonstrates the concept of recursion in a variety of contexts, such as investing over time, sorting a list, and population growth. It shows the importance of observing repeating patterns and using those patterns to develop recursive formulas or algorithms to simplify complex problems. This unit was probably the one that the PD teachers found to be the most abstract and challenging.
- **Unit 7: Tomography:** This unit provides a general background on computer generated tomography and studies how CT scan images are created using 3-D reconstruction of objects using 2-dimensional pieces (slices) of the object. It

engages the PD teachers in using computational thinking to deduce 3-D structures based on 2-D projections. For those teaching physics, the unit includes an optional section on Beer's Law as it is applied to tomography.

- **Unit 8: Cryptography:** This unit illustrates computational thinking through concepts of cryptography. It introduces simple permutation ciphers and challenges PD teachers to “crack the code” to reveal an encrypted message. In so doing, it shows that what is complex in theory may not be so complex in practice. The unit goes on to introduce the RSA method for encryption that is currently used to secure online transactions.
- **Unit 9: Streaming Data:** This unit looks at some of the computational thinking tools required for video streaming. It considers such things as how to detect errors in transmitted messages and fundamental tradeoffs in algorithm design, such as the tradeoff between accuracy and running time. The unit looks at the use of “check digits” for error detection and more advanced methods such as Hamming codes to both detect and correct errors (One of the PD teachers planned to include this material in her physics class in discussions on how electronic devices send and receive information).
- **Unit 10: Weather Generators:** This unit deals heavily with ideas relating to uncertainty in data and simulation. A weather generator produces a “synthetic” time series of weather data for a location based on the statistical characteristics of observed weather at that location, so it can be thought of as a simulator of future weather based on observed past weather. This unit engages the PD teachers in exploring and reasoning about weather trends using a weather generator.

Each unit was designed to take two to four hours to complete, with three as the goal. Of the ten units that make up the course, the first six units are required components of the course. Once a participating teacher finished these six units, they selected two of the remaining four units to complete the course. The first six units provide examples of computational thinking in a variety of settings, and they touch on what we believe to be a core set of CT concepts. The remaining four “selectable” modules cover higher-level or more specific concepts, so course participants could select the two that most closely aligned with their teaching and/or interests.

The online course uses compelling examples to demonstrate CT concepts such as modeling and abstraction of complex problems, reformulating and decomposing difficult problems into simpler ones, representing and managing problem data, designing efficient and effective procedures, and assessing heuristic procedures. *The notion that computing is a tool that offers capabilities that can augment and enhance human thinking is a recurring theme woven throughout the course, as is the notion that most teachers already include many CT practices in their teaching. An important goal of the PD was to help teachers to recognize examples of computational thinking and then label them for their students.*

By leveraging the existing VCTAL materials and engaging a team of seasoned

authors who had been involved in developing or testing them, we were able to have the course ready for pilot testing in early 2019.

2.2. CTPD Course Delivery

Participating teachers were recruited at eight geographic sites nationwide with the PD offered over four weeks (typically in the summer) or eight weeks (during the academic year). **Table 1** provides details on the location and timing of the groups. In total, the eight cohorts included 172 teachers, most of whom were practicing teachers of science or mathematics in high schools. The first cohort pilot tested the course and included both in-service and pre-service teachers. Several sites also included teachers of other subjects or grade levels who participated based on their interest, including an elementary school teacher and several middle school teachers.

Table 1. Professional development sites and format.

Site	Site Total participants	Initial workshop	Location and duration
1	21 prospective and practicing teachers	Face to face	Nevada, MO 8 week pilot course February 12-April 21, 2019
2	21 practicing teachers	Face to face	Pittston, PA 4 week summer course July 8-August 4, 2019
3	23 practicing teachers	Face to face	Oklahoma City, OK 4 week summer course July 18-August 17, 2019
4	21 practicing teachers	Face to face	Helena, MT 8 week course September 7-November 1, 2019
5	24 practicing teachers	Face to face	Albany, NY 8 week with winter break November 11, 2019-January 30, 2020
6	22 practicing teachers	Synchronous online	Logan, UT 4 week summer course July 9-August 6, 2020
7	19 practicing teachers	Synchronous online	Groton, MA 4 week summer course July 15-August 11, 2020
8	21 practicing teachers	Synchronous online	Boston, MA 8 week course October 3-December 6, 2020

As mentioned above, the course was designed to begin with a face-to-face in-person workshop to bring participants together to meet one another, create excitement about CT within the group, introduce the online platform, and lay the foundation for a geographically centered community of teachers learning CT together and then sharing it with their students. When the pandemic struck, holding the initial face-to-face orientations became impossible, and our hope to establish geographically based communities of CT learners also faded. Nonetheless, the fact that our program was designed to be conducted primarily online meant that it could be readily adapted to be fully online for the final three sites.

After the initial workshop, participants proceeded more or less at their own pace through the materials and related assignments. Units were opened on a fixed schedule for each group in order to maintain some level of group cohesion while still allowing self-pacing. Because the units included group discussion boards, it was beneficial to keep the enrolled teachers proceeding at a similar pace.

Like much professional development, the curriculum aimed to enhance teachers' content knowledge in CT, as well as their knowledge of different instructional activities that might be appropriate for high school students, pedagogical content knowledge. Most of the activities were "hands-on" or inquiry-oriented, engaging the teacher-participants and potentially their future students in real world problems: using networks to anticipate traffic congestion, figuring out how much money would be in a college savings fund that was started in 2000, considering the pros and cons of carbon pricing policies to encourage consumers to buy electric vehicles. As their comments across units (Wilson et al., 2023) and sites demonstrate, participants spent a great deal of time engaged in the content. The post unit questions allowed them to consider where computational thinking was in the unit, and whether the activity that they had engaged in as a learner would be appropriate to use with their own students. Of the 172 teachers who participated in the professional development, only five failed to complete at least 80% of the assignments and the vast majority completed well over 90% (Wilson et al., 2023).

Throughout the course, teachers were asked to comment on what concepts or activities from each unit might be applicable to their own classrooms, and they had many ideas about both how to use entire units or specific activities with their students. They also described how they might adapt the materials, including tools like spreadsheets, to their disciplines and classes.

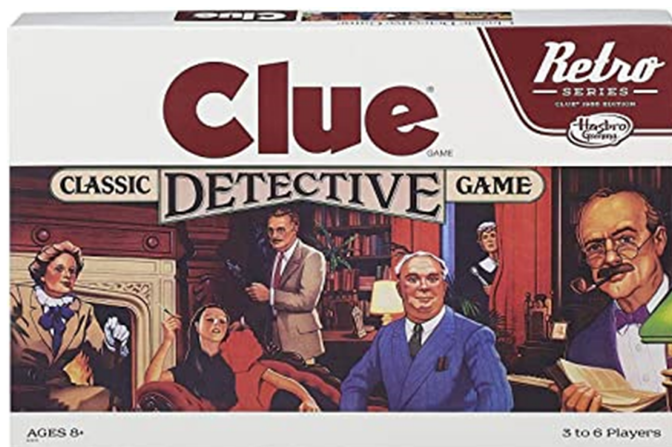
3. Empowered, Teachers Invent Their Own Additions of CT to Their Classes

Upon completing the program, participants were asked to submit examples of how they had used and/or adapted the materials for their own classroom use. For instance, several participants across different cohorts reported on designing activities that used spreadsheets. The examples provided were then posted on Canvas as a course called Implementation of CT in the Classroom for others to use in their classes. Three quarters of the examples were science examples and a few are highlighted in the next section.

This paper discusses empowering high school teachers through professional development opportunities around computational thinking where the goal of integrating computational thinking (CT) into existing practice shifts attention away from a particular instructional approach to providing teachers with the opportunity to fold adapted CT materials into their existing practice, thus teachers become agents. From the participants' perspective, DIMACS CTPD achieved its primary goals of expanding teachers' abilities to think computationally, especially in terms of decomposing and testing out various solutions; and they gained familiarity with a wide range of activities and units that they could adapt for use in their classrooms (Wilson et al., 2023). A number of examples of science teachers, who have invented their own additions of CT to their courses are provided, including one from a third grade teacher.

Daniella Duran, a high school Chemistry teacher from Valencia, California, teaches an advanced class in nanotechnology and took the CTPD in the summer of 2020 when it was fully online. She has worked with UCLA to develop nanoscience curricula for other high school teachers and is no stranger to classroom innovation. She decided to employ her new CT skills to show her students how to develop their own nanotechnologies in small teams using CT to “model” frog’s saliva using Elmer’s glue, Borax, and the assistance of a spreadsheet (DIMACS, 2020). Mixing Elmer’s glue and Borax with water produces a sticky and pliable substance akin to Silly Putty (or frog saliva). Durand’s students do a lab in which they mix these ingredients with water, in varying amounts, until they find a mixture that mimics the properties of frog’s saliva. For each mixture, students measure a number of properties, such as resistance and elasticity, and enter their data into a spreadsheet equipped to calculate Young’s modulus, which describes the elastic properties of a solid under tension. Among, other things, the lab experiment shows how data can be collected, analyzed, and manipulated to solve problems, and that how those processes can be aided by computational tools and automation.

Following the design of the game *Clue*, **Brea James, a high school physics teacher in Boonsville, Missouri,** who participated in the pilot professional development site in Nevada, Missouri, asked her students in her physics class to solve the mystery of who killed Miss Mercury in what Room with what instrument. The students had to uncover eight clues to find the answer to this question. Each clue was wrapped in a different cipher or secret code that first had to be broken. They learned how to solve the problem using CT strategies and what they had learned from the cryptography module. For example, one clue was wrapped in a Caesar cipher as UXOHU (ruler), another as a Polybius Square cipher as 14/42/22/42/15/15/33 (Dr. Green). Even one clue was written in Morse Code (*Can you find the shift in the Caesar cipher and the matrix used in the Polybius cipher?*). Teachers are often positioned as targets or agents of reform in professional development (Sykes & Wilson, 2016). One high school allowed a teacher to take her students to an escape room nearby and apply their CT knowledge to escape in the fastest time. They earned third place for the fastest time.



Cryptography Murder Mystery

A murder has been committed in the science department at a nearby school. Your job is to decode the clues to find the **identity of the murderer**, the **murder weapon**, and the **room in which the murder took place**. After a quick scan of the scene, you are able to narrow your list down to six suspects, weapons, and locations. You also find a handful of clues that have been encoded using a variety of different cryptography techniques.

Suspects

Mrs. Gold	Dr. Green	Mr. Blue
Dr. Nickel	Miss Mercury	Dr. Silver

Locations

Room 17	Room 19	Room 21
Room 23	Room 25	Room 27

Weapons

Meter Stick	Electronic Balance	Hydrochloric Acid
Ruler	Calculator	Beaker

Group Members:

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Conclusion:

Suspect	Location	Weapon

The [Cryptography Murder Mystery](#), published online by physics teacher Joe Cossette, was adapted by physics teacher Brea James for use by her Boonsville High School students.

Even though the CT professional development PD was designed for high school teachers, Anna Mello, 3rd grade teacher in Lanesborough, MA, requested to participate in the Albany NY site. Related to the *Privacy module*, she showed how CT could be used in her third-grade class to identify who was a

specific Revolutionary war hero using data collection and pattern recognition. She taped large pieces of drawing paper, each prepared by a student listing ten characteristics or clues about the identity of a Revolutionary war heroes in Massachusetts. Each hero profile contained similar information, such as their date of birth, gender, and their role in the Revolutionary War. Each student who prepared a profile obviously knows who their hero is.

The problem is for each student to determine who the other nine are. One girl suggests looking in the index in the back of their text book to determine who the other nine are. These students are learning how to ask questions, how to work in teams, and how to think for themselves, and test hypotheses. So engaged were the students that they weren't even aware of the bell ringing to end class. A CTPD high school teacher had her students try to determine how much information existed on them online and used it to advise them on giving away too much personal data online.

Helen Bosch and Christine Thomas, Biology teachers in Helena, Montana, developed a computational thinking activity in their PLTW (Project Lead the Way) Biomed 3 classes in two different high schools. They developed an activity that they called “who should receive the organ” similar to the computational thinking activities in the *Heart Transplant* module. In the PLTW activity, the students are given a resource sheet that contains thirteen situations. Each situation describes a pair of patients that need a kidney. The situation describes the patient's ages, time on the transplant list, and more, and extraneous information such as the person is an inmate or mother of three. The students work in groups and they must choose who gets the kidney of the two patients. After they decide who gets the kidney of the two, they read about organ allocation policies set for the by the National Organ Transplant Act (NOTA) and the Organ Procurement and Transplantation Network, and they decide if following NOTA would change the allocation. The students would then create an algorithm, a computational thinking activity, based on four criteria:

- Compatibility of the donor and recipient;
- Geographical proximity of the donor and recipient;
- Time on the waiting list;
- Age of the recipient (children get preference).

After applying the algorithm to all 26 patients, they gave each a score and a ranking. They shared their algorithms with the whole class and their patient scores. They compared scores and found they were very similar across all algorithms.

4. Conclusions

This paper illustrates how teacher professional development can be designed so teachers develop their own understandings of computational thinking and gives them the opportunity to apply these understandings to their own discipline-based classes and empowers teachers to think outside the box while doing so.

Few researchers have reported on professional development for teaching computational thinking. The paper by Caskurlu et al. (Caskurlu et al., 2021) gives an indication of the use of computational thinking to improve teacher competencies. More research is needed.

All twelve CT modules are available through COMAP free. Teacher versions require registering with COMAP. The professional development courses are available on Canvas by contacting Margaret Cozzens.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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