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Work in Progress: Integrating Computational Thinking in STEM Education through a Project-based Learning Approach

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Work-in-Progress: Integrating Computational Thinking in STEM Education through a Project-based Learning Approach

Abstract: This work in progress describes the design of a project-based, STEM +C (Computing) curriculum for 4th to 6th grade students in an afterschool setting, which is part of a large NSF-funded STEM+C project. The paper reports the preliminary outcome of the implementation of the first two STEM+C projects that focuses on student attitudes toward STEM and the computational thinking revealed during students' scientific inquiry and problem solving processes.

Background

Computational thinking (CT) is a fundamental skill that is equivalent to reading, writing and arithmetic skills [1]. CT involves problem solving, systems design, and "understanding human behaviors" [2]. CT is also a metacognitive process that consists of sub-skills and dispositions, which provide students the ability to analyze scientific patterns and model complex phenomena [3]. Thus, CT is considered to be the "third pillar" of scientific practice [1] and plays a critical role in scientific inquiry and problem solving [4].

Currently CT is widely missing in K-12 STEM education [5], [6]. There is also a lack of qualified K-12 teachers to teach computing [7]. In terms of research, the development of CT in K-12 students has not been sufficiently investigated [6]. Research on how to integrate CT into STEM education, especially on how to develop CT in K-12 students, is needed. Similarly, how to prepare K-12 teachers for such integration is also a priority.

The development of CT in students is closely related to their STEM learning [8]. This is due to links between CT and science, technology, engineering, and mathematics (STEM), especially for problem solving and scientific reasoning [9]. This study describes the design of a project-based, STEM +C (Computing) curriculum for 4th to 6th grade students in an afterschool setting that is part of a large NSF-funded STEM+C project. The paper also reports the preliminary outcome of the implementation of the first two STEM+C projects, part of the STEM+C curriculum.

Theoretical framework

Wing [2] views CT as process and logic rather than programming and coding. In this study, we focus on two main aspects of CT based on Wing's perspective: (1) thinking at multiple levels of abstraction during problem-solving processes; and (2) communicating ideas and knowledge in computational terms during problem solving and hands-on inquiry. To facilitate our integration of CT into STEM inquiries, we highlight specific CT components for student hands-on inquiry and problem solving (Table 1). Some elements in Table 1 originated from Brennan and Resnick's Framework of CT [10], which consists of CT concepts, CT practices, and CT perspectives.

Table 1: Computational thinking components

CT Component	Description
Vocabulary and terminology	CT vocabulary, such as variables, data, modeling, testing and debugging, iterative. [6], [10]
Abstractions	Reducing complexity to make sense of things. The abstraction process allows building complex designs and large systems. [11], [12]
Decomposition	Simplifying problems or specifying solutions. [7]
Algorithms	Applying specific set of tools or sequence of steps (processes) to solve problems. [13]
Automation	Utilizing programs to refine, revise, or reexamine abstracted data or work in progress. [11], [14]
Conditional logic	Using strategy such as an "if-then-else" construct to clarify problems and solutions. [2]
Heuristics	Applying experience-based strategy that facilitates problem solving, such as "trial and error". [15]
Data collection	Gathering data to define or solve a problem. [14], [16]
Data analysis and representation	Exploring data to find patterns, causes, trends, or results to facilitate the knowledge construction and problem solving. [14], [16]
Simulation and Modeling	Manipulating data or concepts through controlled programs or exercises or creating such programs for data manipulations. [14]
Communication	Written and oral descriptions supported by graphs, visualizations, and computational analysis. [17]

For K-12 students, an example of CT revealed in their STEM inquiry could be working together to gather data about different types of earthquakes (i.e., data collection). Another example could be working out a plan to build a robot for detecting life on Mars (e.g., design, sketch, build a prototype, test, redesign, rebuild) (i.e., decomposition).

Design of the STEM+C curriculum

The design of the STEM+C curriculum was guided by a project-based learning (PBL) approach. PBL is "a systematic teaching method that engages students in learning knowledge and skills through an extended inquiry process structured around complex, authentic" questions [18]. The PBL approach enables the design of hands-on activities that give students the opportunity to investigate relevant topics or problems and to learn through active creation of final products. In PBL, all learning activities and objectives are driven by an overall guiding question. At the end of a PBL unit, students showcase their final product, often through a final competition or exhibition.

The STEM+C curriculum that we designed so far consisted of two PBL projects. One was Life on Mars and the other was Building Earthquake Resistant Bridges. Both projects had an overall guiding question and sub-questions that drove the learning objectives and learning activities in each project. Both projects also required students to integrate science, technology, engineering, and math (STEM), as well as CT (STEM+C), to solve the overall driving question. Both projects had an extended inquiry period of eight weeks (two 90-minute sessions per week). The following table lists the essential components of each STEM+C project in the form of the PBL-guided learning/inquiry.

Table 2: STEM+C projects with essential PBL elements.

STEM+C Project	Life on Mars	Earthquake and Boise River Bridge Design
Project Description	In groups of 2-3, students research different forms of life and the environment of Mars. Students design and assemble a robot to detect life on a simulated Mars.	In groups of 4-6, students research earthquakes and bridges. Students design an earthquake resistant bridge. Students build and test their bridges under simulated earthquake conditions.
Subject Content	Engineering, Science, Math, Computer Science, Technology	Engineering, Geoscience, Math, Technology
Learning Objectives	Students investigate life on Mars and how it can be detected; students design and build a robot to detect life on Mars.	Students investigate bridges and earthquakes; students design and build a bridge and test it under simulated earthquake conditions.
Driving Question	How can we detect life on Mars using a robot?	How can we build a strong bridge for the Boise River to resist earthquake forces?
Sample Sub-questions	What does life consist of?; What is the environment on Mars?	What is a bridge and why do we need it?; How is a bridge designed?
Final Product	An assembled/programmed robot by each team	A bridge designed and built by each team; Presentation on their bridge design
Sample Hands-on Activities	Researching information on Mars; assembling and programming a robot	Researching information on different types of bridge; designing, building and testing a bridge
Assessment	Final completion on which robot detects the life in the shortest time.	Final competition on which bridge is the strongest in resisting earthquake forces.

In the Life on Mars project, students were directed to learn and apply CT and STEM subject knowledge focusing on robotics and programming. Students assembled robots using Lego Mindstorms robotic kits, and programed the robots with EV3 software featuring drag-and-drop programming interface. In the final week, students showcased their robots, which were designed to detect whether there was life (a green symbol) on a simulated Mars built by the researchers. In the Building Earthquake Resistant Bridges project, students were directed to learn and apply CT (see Table 1) and STEM subject knowledge focusing on engineering design and bridge building. Students built bridges using K'Nex building kits. In the final week, students showcased their bridges and competed for the best bridge design.

Since both projects focused on hands-on problem solving, we designed a Problem Solving Chart (Figure 1) based on the engineering design process [19] to help students understand and learn to use CT. The Problem Solving Chart consists of seven stages of solving a problem: identify the problem, research the problem, develop possible solutions, select best possible solution, build a prototype, test and evaluate prototype, and redesign as needed. The CT components were also mapped with each stage of the problem solving process. Depending on the learning activities planned, students learned to use different CT each week. For example, at the beginning of the program, students learned to collect data and analyze data regarding life and Mars. At the near end of the eight-week program, students learned and applied algorithms, data collection, communications etc. to design, build, test and redesign their robots and bridges.

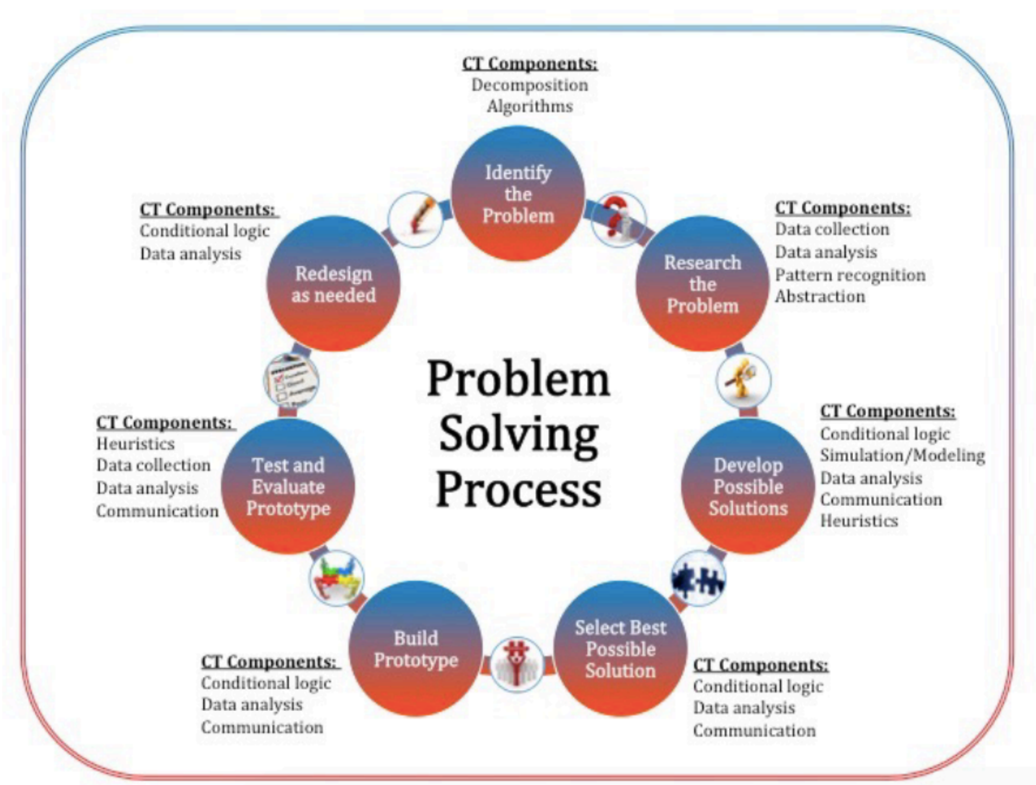

Fig. 1 Problem solving chart

Research design

The implementation of the two STEM+C projects took place in late afternoons at four Title 1 elementary schools in partnership with the schools' serving community centers. In general, a school is designated as a Title 1 school if at least 45% of its students receive free or reduced lunch. Seventy-two students from 4th to 6th grades were recruited for the study. The local school district helped recruit a total of twelve teachers to work with the students in small groups of three to six. During the 2017 spring and fall semesters, 72 students and 12 teachers worked with the project team implementing two STEM+C projects with each project being implemented once at two different schools.

In this study, we focused on how student participation in the STEM+C projects helped students develop CT and the impact of students' STEM+C experience on their attitudes toward STEM learning. A student attitude toward STEM survey [20] was given at the beginning and end of the eight-week program. The development of the STEM survey was partially supported by the National Science Foundation and was well validated [21]. The STEM survey has three subject categories, Math, Science, and Engineering and Technology (engineering and technology were grouped together into one category) and was intended to examine students' attitudes as well as self-efficacy related to STEM. Students were videotaped working in small groups for the whole project period of eight weeks.

Data analysis

We analyzed the pooled survey data from 53 participants who completed both the pre- and post- survey to examine if students' participation in the STEM+C projects affected their attitudes toward STEM. We also reviewed and analyzed videotaping of students' hands-on inquiry and problem solving for evidence of CT. We adapted Sfard's [22] discursive framework, which focuses on learning as a change and examines scientific discourses in students, to examine the development of computational thinking in students. Due to the close relationship of computational thinking and scientific reasoning, it was appropriate to use an adapted Sfard's framework to examine the development of CT in students.

There are four characteristics of scientific discourse in Sfard's framework: 1) *word use* (words and their use), 2) r*outines (*well-defined repetitive patterns and characteristic of the given discourse*), 3) endorsed narrative (spoken or written descriptions of objects)* and 4) *visual mediators* (visual structure to provide meaning of an object). For *word use,* our analysis focused on student's use of CT language, such as *speed*, *distance*, *variable*, *scale, materials, constraints,* and *magnitude*, to explore how knowledge is communicated and constructed through interactions in small groups, which is equivalent to the CT vocabulary and terminology in Table 1. For *routines*, we focused on how students approach solving a problem, such as abstraction and decomposition of a problem. For *endorsed narrative*, we focused on such CT components of communication, data collection and analysis. For *visual mediators*, we focused on CT components related to data structures/ analysis/representation and simulations and modeling.

As students' learning was driven by the overall and sub-questions in PBL-guided inquiry and problem solving, we analyzed the videotapes/segments based on specific sub-questions in each of the beginning, middle and final or near final weeks of the eight-week program. We chose to analyze the video recordings of students' work from weeks 1 (at the beginning of the project), weeks 4 (in the middle) and weeks 7 and 8 (the end or near end with same sub-questions) following the project structure from acquiring/inquiring fundamental disciplinary knowledge to higher problem-solving activities.

Results

Based on the student attitude survey, there was a significant difference between students' attitudes toward Math ($p= .019$) at the beginning and end of the eight-week program. Students had a much more positive attitude toward math after they completed the STEM+C projects. However, there was no significant difference regarding students' attitudes toward Science, and Engineering and Technology.

Due to the dropping out and occasional no-show of some participants, we could not analyze the videotapes and report CT based on each individual participant throughout the program. Therefore, we reported the findings of CT based on the learning objectives (sub questions in the curriculum) to show the progression of student learning. Based on the analysis of videotapes, students demonstrated various CT components during their scientific research inquiry, as well as problem solving. The following table illustrates the kinds of CT components based on the sub-questions analyzed. We also made notes on the connections between the analysis results and the CT components described in Table 1.

Table 3: CT in students' scientific inquiry and problem solving

Life on Mars	CT category	Week 1: Sub-question: What is a robot and what are the components of a robot?	Week 4: Sub-question: How do we assemble and program our prototype?	Week 7 & 8: Sub- question: What is the most efficient way to explore Mars?
	Word use (CT vocabulary and terminology)	Computer chip; computer brain; program; sensor; motor; Legos	Build; attach; connect; touch sensor; block; program; sequence; speed; turn	Move; rotations; degrees; measurement; program; simulation
	Routines (abstraction, decomposition, communication etc.)	Whole group discussion; between group discussion	Whole group discussion; between group discussion; try to see what works	Whole group discussion; testing; identifying an issue(s); reprogramming;

				retesting (physical actions)
	Endorsed narrative (abstraction, data collection and analysis, decomposition etc.)	What does a robot do; what are the parts or pieces; can a robot think; what does it mean to be able to think; how and why	Think about the blocks you can use and how you can use them; research your program	Talk about ideas; what we are going to do; how we are going to solve it; take note of what did and didn't work
	Visual mediators (simulation and modeling, communication etc.)	Journals; Google slides; Videos	Journals; Google slides; Lego EV3 robots; Lego EV3 program	Journals; Lego EV3 robots; Lego EV3 program; simulation
Bridge Build-ing	CT category	Week 1: Sub-question: What are the different types of bridge	Week 4: Sub-question: What are the damages of earthquake?	Week 7 & 8: Sub- question: How can we build a bridge for the Boise River that is strong enough to resist earthquake forces?
	Word use (CT vocabulary and terminology)	Steel; sturdy; stone; metal; vulnerable; shake; thicker; wider	Strong; shake; radar; lava; inner-core; outer-core; destruction	Tower; deck; shake; stable; triangle; square; money' rod; stabilize; testing
	Routines (abstraction, decomposition, communication etc.)	Whole group discussion; simulation; between group discussion	Whole group discussion; instructor-led discussion	Modify; test; retest; rebuild
	Endorsed narrative (data collection and analysis, heuristics, decomposition etc.)	Difficult to travel; hard to get to work; cross river	Cause structures to collapse; deaths; landslides; tsunamis; volcano	Cost money; strong enough to resist earthquake

	Visual mediators (simulation and modeling, communication etc.)	Recorded notes	Journals; Google slides; Google Classroom	Sketches of bridge designs

The participants in this study were all from Title I schools. Most of the participants had not had the opportunity to participate in such a program and had not played with the Lego Mindstorms or K'nex building kits which were used in the projects. The STEM+C projects provided students a learning environment where they could explore, learn and apply CT during their scientific research inquiry and problem-solving. For example, students communicated their knowledge and problem solving strategies via *word use* of CT terminology and language. Students communicated their design and redesign of robot and bridge strategies via *routines* of data analysis and representation, and algorithm for solving problems.

This study contributes to the design of STEM+C curriculum for integrating CT in K-12 STEM learning. It also contributes to the assessment and evaluation of CT in K-12 students.

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