Teaching Computational Thinking and Spatial Visualization in K-12 with 3D Weather Visualizations

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***Abstract*—This Innovative Practice Full Paper presents a K-12 teacher training workshop for computational thinking instruction. Computational thinking refers to a set of skills that are necessary for success in engineering and science careers. Teaching computational thinking skills prior to university-level enrollment helps students be more successful in their degree programs. Our project serves as an attempt to innovate science education by designing and testing data-driven, scientific inquiry experiences that integrate teaching and learning of atmospheric science with computational thinking and practices in authentic, innovative, and effective ways. In this paper, we describe our design process for developing authentic computational thinking and spatial visualization modules for the two-week computational thinking professional development that uses 3D weather visualizations to train K-12 teachers in eleven computational thinking and spatial visualization skills.**

Keywords—computational thinking, spatial visualization, K-12

I. Introduction

Computational thinking (CT) and spatial visualization (SV) refer to a set of skills that are essential to master in order to become an engineer. CT refers to a set of problem formulation and solving skills that allow one to conceptualize data and create algorithmic steps to solve problems with computers [1]. While rooted in problem solving for computer science, CT skills are broadly applicable and useful within other fields [1]. CT is especially relevant for engineering as we increasingly rely on computers to assist with engineering problem solving. Due to the importance of CT skills, over the past decade, CT has been recognized as key skills for K-12 education; CT was included in the 2012 Next Generation Science Standard as one of its Disciplinary Core Ideas for Integrated K-12 and STEM instruction [2] and the 2016 White House's Computer Science for All initiative [3]. Similarly, SV skills have long recognized as critical for engineering. SV refers to skills necessary to create a 2D or 3D mental map of on object and mentally manipulate the object (e.g., rotate). The engineering education research community has long acknowledged SV as an important and underdeveloped skill [4], with several approaches such as workshops or first-year courses used to strengthen SV skills for new engineering students (e.g., [5,6]). Clearly, CT and SV are critical skills that engineering students must master.

The importance of these skills has motivated a multitude of attempts to embed these skills within primary and secondary education curricula. CT skills have been primarily embedded within course topics such as robotics (e.g., [7]-[10]), unplugged programming activities (e.g., [11]-[13]), and traditional programming (e.g., [14]-[17]). Since many public school systems in the rural areas of the United States have limited numbers of engineering, robotics, and computing courses at the K-12 level, there is a need to embed computational thinking and spatial visualization into existing courses within the curriculum. Math and science classes have become new targets, but often many implementations use science as a mere application to teach programming [18]. For example, a K-2 implementation of CT skills in a science class focused on teaching algorithmic thinking, sequencing, decomposition, and debugging in the context of programming a robot to move on a map that illustrated the water cycle [19]. While students did learn CT skills and the water cycle sequence, they were using CT skills in the context of computer science and programming, and not in the authentic ways that an earth scientist might use the skills.

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We advocate for a more authentic integration of CT and SV into science instruction by developing an integrated curriculum in conjunction with subject matter experts to incorporate the ways that the experts genuinely use specific CT and SV skills. Further, we posit that some disciplines, including engineering, are disciplines where spatial and thus CT and SV skills are inextricably linked parts of the problem solving process (i.e., *spatial computational disciplines)*. Thus, teaching CT and SV within the *spatial computational disciplines* that are part of K-12 standards will prepare students to enter *spatial computational disciplines* at the university level. Thus, our work focuses on creating teacher training to authentically integrate both CT and SV skills into science curriculum. We selected meteorology as our *spatial computational discipline* and developed a summer workshop for secondary science teachers to train them to teach CT and SV within their curriculum, which includes weather topics.

II. Application Domain: 3D Weather

A. *Movtivation for Teaching CT and SV through Weather*

We are using weather as our context for teacher training because it is a science phenomenon that is universally familiar to all: everyone has some experience with weather. Both teachers and children have experienced weather such as feeling light rain on a misty day, hearing thunder produced during a thunderstorm, watching snow fall on a winter day, and more. Further, atmospheric science is the only science that concerns everyone and everyone sees on TV daily. The general public has seen temperature maps and radar displays; they have learned about percentages and probabilities through forecasts and predictions. All these experiences provide opportunities for learning since teachers and students can connect their own experiences (prior knowledge) with a lesson on weather. Finally, in addition to connecting to students' prior knowledge of weather when teaching, extreme weather and climate events can be used to trigger student motivation and interest. Teachers can discuss why a recent storm produced significant ice and sleet rather than snow, or why some storms are more likely to produce tornados.

B. *Data and Tools Available for Teaching 3D Weather*

Weather is an ideal application for teaching CT and SV at the K-12 level because it inherently requires data analysis and visualization for accurate diagnosis of atmospheric processes and improved weather prediction. Daily weather data from the North American Mesoscale Forecast System (NAM) is freely available through the National Oceanic and Atmospheric Administration (NOAA) Operational Model Archive and Distribution System (NOMADS) [20]. Additionally, there exist readily available large-scale global, regional, and local modeled weather data. The Integrated Data Viewer (IDV) is a free and open-source computational software tool developed by Unidata for analyzing and visualizing geoscience data [21]. IDV can display and manipulate geo-referenced datasets of various data types (e.g., observed, simulated) and support a variety of data visualization methods (e.g., contours, dynamic color mapping). It allows users to interactively slice, dice, and probe data creating cross-sections, profiles, and animations. Free daily data combined with a free data visualization tool allow teachers to develop custom learning modules for their classrooms based on current events that their students have experienced.

C. *Teaching CT and SV through 3D Weather*

In this section, we provide an example of how CT and SV er could be integrated into a middle-school science classroom based on the "polar vortex event of January 24-29, 2019 that occurred in the midwestern United States and eastern Canada. The learning module would be related to the atmospheric science topic of "cold front" within a theme of "Distribution and Movement of Air." Framing the module within the learning sequence of Engage, Model and Observe, Explain and Predict, and Communicate results in the following module design summary:

- <u>Engage</u>: Teachers can begin the module by engaging students in research to report findings about the record-breaking cold in the Midwest in January 2019 with the initial questions of: What caused this severe cold? How did it effect people and towns? How can we predict it? After this, the teacher can formally introduce cold fronts and other weather conditions related to air movement.
- <u>Model and Observe</u>: Students will be guided to access the free NOAA NOMADS weather datasets, and visualize relevant atmospheric data using IDV. Teachers can guide students to visualize and analyze multiple datasets from one day or even several days in a row and generate a time sequence animation of 3D images to allow students to see the development and evolution of the atmosphere before and during the cold air outbreak. Students can also generate parameter plots or graphs along with the 3D models and manipulate the 3D models to explore patterns and processes that are important to the generation and evolution of the atmospheric system.
- <u>Explain and Predict</u>: In this phase, based on observation of and experiences with the 3D data analysis and computational visualization models generated by IDV, students will refine their answers to the initial research questions.
- <u>Communicate</u>: Students will organize and communicate their findings and conclusions by incorporating their observation of and experiences with the 3D data analysis and computational visualization and models generated by IDV. Their answers will provide explanations of the generation and evolutions of the cold air outbreak and how such severe weather events can be predicted.

CT and SV skills could be integrated into the above framework at any stage, but they are most easily taught during the Model and Observe stage with students practicing the skills (with teacher feedback) during the Explain and Predict stage.

D. *Authentic CT and SV for 3D Weather*

To determine which CT and SV skills should be taught in the meteorology context, we conducted a literature review of computational thinking studies within K-12. We reviewed 109 articles from 97 CT-related projects that received funding through the National Science Foundation's STEM+C program. Additionally, we used the key words "spatial thinking" to search peer-reviewed journals and conferences from 1965 – 2020.

From these articles, we identified 64 traditional CT skills. We counted the number of articles that each CT skill appeared in to develop a list of the ten most frequently cited CT skills. An expert panel of meteorologists reviewed this list and identified four of these skills as critical meteorology competencies. They provided definitions of these CT skills that authentically embed the skills in meteorology.

- Task Decomposition: The ability to diagnose a complex system by decomposing tasks contributing to overall storm motion (e.g., rotation, wind direction, advancing fronts) to determine the overall path of a storm.
- Disembedding*:* The ability to process visual information in complex or chaotic data by selectively focusing on specific, important features or patterns (i.e., the signal) and ignoring distracting, non-essential patterns (i.e., noise).
- System thinking: The ability to understand relationships and interactions between the atmosphere, water, and energy from the sun in the climate systems.
- Generalization: The ability to identify patterns, similarities, and connections within the climate system.

Additionally, based on the above-described literature review, we identified six types of CT skills related to SV skills. The expert panel identified all six of these skills as critical meteorology SV competencies:

- Mental animation: The ability to infer motion from information given in static 2D or 3D images.
- Perspective taking: The ability to envision how something would appear from different vantage points, orient oneself to the external framework of the surrounding environment, and coordinate spatial relationships from different viewpoints.
- Object location memory: The ability to remember the spatial locations of previously seen objects or phenomena.
- Spatial reasoning: The ability to construct mental presentations for spatial objects and reason about their relationships and transformations.
- Visual penetrative ability: The ability to visualize the cross section of the interior of an object as it is sliced at different locations and at different angles
- Spatial orientation / spatial perception: The ability to identify the position or direction of objects or points in space, and to recognize and comprehend the relationship between one's location in space and objects in this external environment.

Our 3D Weather training workshops for K-12 teachers were designed to focus on these four traditional CT skills and six SV skills.

III. 2021 Workshop Implementation

A. Workshop Design Overview

The primary training for K-12 teachers consists of a two-week workshop during the teachers' summer break. The first week of the workshop was designed as an online learning experience and focused on content knowledge in CT/SV practices and four meteorology themes (temperature, moisture, pressure and wind, and mid-latitude cyclones). The second week was designed as a face-to-face experience with training related to 1) accessing and retrieving weather data from publicly available online sources, 2) data analysis, interpretation, and visualization with IDV, 3) 3D weather learning modules related to the four at atmospheric science themes, 4) pedagogies and strategies for implementing 3D Weather learning modules and fostering CT and SV throughout the modules, 5) processes and principles to develop additional CT and SV in atmospheric science learning lessons. The face-to-face workshop component ended with teachers showcasing their individual atmospheric science learning lessons that were customized to their own school district learning outcomes and plans.

B. Week 1: Online Workshop Design

The self-paced, online workshop was designed to be completed over five days. Each days' activities were organized in a module that focused on a specific topic: CT/SV skills, temperature, moisture, pressure and wind, and mid-latitude cyclones.

For the CT/SV skills module (Day 1), teachers were provided an overview listing of the CT/SV skills (similar to information presented in section II.D. of this paper). They were also provided a narrated slideshow that included definitions of CT/SV and contextualized the terms within current literature. Then, the teachers learned about each term through graphical examples of the skills. This module was not contextualized within meteorology, but instead defined the four CT skills and six SV skills broadly. At the end of the module, teachers completed a knowledge check (i.e., section quiz).

For the weather modules (Day 2-5), teachers were provided instruction on meteorology topics designed by meteorology experts. The material was not contextualized within the CT/SV skills, but rather a designed as an introduction or refresher to meteorology topics and vocabulary that would be critical for the second week workshop. For example, on Day 2 the module focused on temperature. Within the module, there were six subtopics: global energy balance, energy balance over oceans and land, vertical temperature patterns, understanding sun angle, seasonal temperature cycles, and diurnal temperature cycles. Each subtopic was taught through an annotated slideshow. For example, the vertical temperature patterns topic contained information on how temperature changes as one moves vertical in the atmosphere and also defined terms such as tropopause, stratopause, mesopause and thermosphere. Examples of slides from the vertical temperature patterns topic are shown in Fig. 1 and Fig. 2. After viewing each of the subtopic lectures, teachers were asked to post questions to a module discussion board that was monitored by research staff who directed the question to the appropriate team expert for response. Following completion of all subtopic lectures for a daily module, teachers completed a knowledge check. Then, as a "thought exercise" teachers reviewed a lesson plan for the daily meteorology topics that included links to school standards (Fig. 3). The lesson plan was designed to teach the days meteorology topics at the teachers' assigned grade-level and was linked to school standards. Teachers were asked to identify ways that the CT/SV skills taught in the Day 1 module could be incorporated into the traditional meteorology lesson plan that was provided. Teachers submitted their results to the "thought exercise" to the discussion board and other teachers and research team members commented on the results.

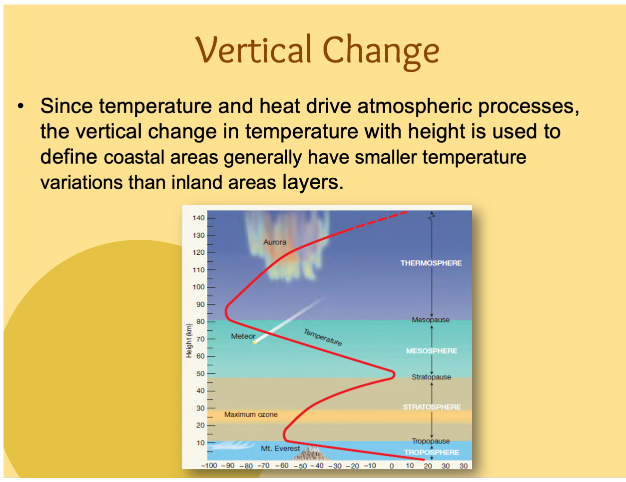

Fig. 1. Vertical temperature patterns slide example: vertical change

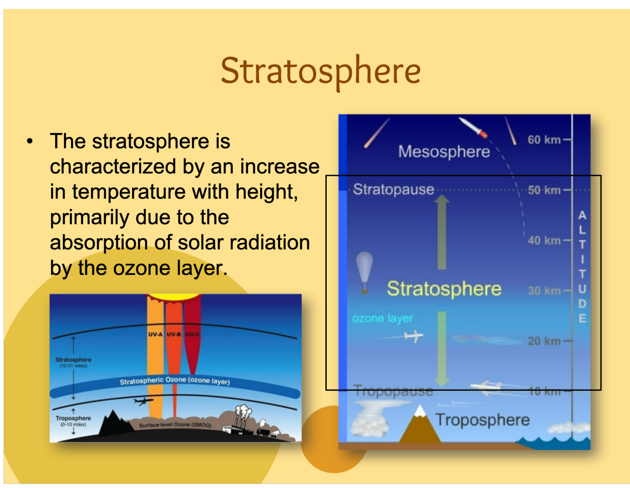

Fig. 2. Vertical temperature patterns slide example: stratosphere

C. Week 2: Face-to-face Workshop Design

The second week of training followed the order of meteorology topics for the first week's online training with days 1-4 focused on temperature, moisture, wind and pressure, and mid-latitude cyclones. Day 5 of the in-person training focused on developing lessons and mini-teaching sessions so the teachers could prepare to teach CT/SV within meteorology during the upcoming school year.

The meteorology topic days were taught by a team consisting of a CT/SV expert and a meteorology expert. For each CT/SV skill, the CT/SV expert would provide a refresher of the general skill, and then the meteorologist would explain how that skill was used by meteorologists to analyze data. Each of the meteorology topic days consisted of a focus on three CT/SV skills with Day 4 repeating spatial orientation / perception due to the critical importance of that skill in meteorology and engineering.

To further illustrate how each of the CT/SV skills were taught each day, consider task decomposition. Generally, the skill relates to the ability to break a complex task or problem into

Lesson Plan 1: Overview of Atmospheric Pressure

Objective 1: What is temperature and how is it generated?

Objective 2: How does temperature influence Earth's conditions?

Grade-level: Seven - Earth and Space Science

Conceptual Understanding: Weather is a combination of temperature, sunlight, wind, snow, or rain in a particular place at a particular time. People measure weather conditions (temperature, precipitation) to describe and record the weather and to notice patterns over time. Temperature and precipitation can change with the seasons. Some kinds of severe weather (hurricane, tornado, flood, and drought) are more likely to occur in certain regions. Meteorologists forecast severe weather so that communities can prepare for and respond appropriately.

Specific School Objectives:

E.7.9A.1 Analyze and interpret weather patterns from various regions to differentiate between weather and climate.

E.7.9A.2 Analyze evidence to explain the weather conditions that result from the relationship between the movement of water and air masses.

E.7.9A.3 Interpret atmospheric data from satellites, radar, and weather maps to predict weather patterns and conditions.

Fig. 3. Part of an example lesson plan for temperature.

smaller, more manageable elements or sub-tasks. Non-meteorology examples could include a doctor diagnosing a patient who is unconscious, or a programmer creating subfunctions to solve a complex problem. Embedded in meteorology, task decomposition relates to the ability to decomposing tasks or interactions that contribute to overall storm motion (e.g., rotation, wind direction, impact of fronts). Following this "refresher" of the skill, the meteorologist further contextualized the CT/SV skill by visualizing data in IDV. Specifically, by visualizing data from March 10—March 14, 1993 that correspond to the progression of the "1993 Super Storm", the expert was able to show how temperature patterns, pressure/wind patterns at 500 hPa and the Jet Stream drove the evolution of the storm from the wave stage through the mature stage.

Coverage of the three daily CT/SV skills took approximately three hours, with the balance of the day dedicated to lesson plan development for the specific CT/SV skills. Teachers completed a research team prepared "teacher guide" that walked teachers through various IDV activities using previously prepared IDV files that could be loaded into the visualization system. The teachers guide modeled activities using the Engage, Model and Observe, Explain and Predict, and Communicate framework described in Section II.C of this paper. Teachers spent time each afternoon discussing how they would convert the teacher materials the research team provided into student materials for their specific grade-level and science topic. Finally, teachers worked in groups to prepare mini-lessons for the Day 5 teaching demos.

On the final day of the face-to-face workshop, the morning was dedicated to teaching demos so that all the teachers could learn from their peers. In the afternoon, teachers had time to refine their lessons based on peer feedback from the teaching demos. The research team also interviewed teachers about their experiences with the workshop and planned the implementation schedule for the upcoming school year.

IV. Workshop Assessment

Our workshops were designed and developed to prepare teachers for to teach CT/SV skills in the context of meteorology using the IDV visualization tool and real, freely available weather data. Specifically for the workshop, the research focused on answering the following research questions:

(1) How does the summer workshop affect teachers' own computational thinking and spatial visualization skills?

(2) How does the summer workshop affect teachers' self-confidence in teaching meteorology through computational thinking and practices?

(3) How does the summer workshop affect teachers' epistemic cognition of teaching meteorology?

To answer these research questions, we administered a survey to 15 workshop participants before and after the workshop. The survey included 13 items measuring the teachers' computational thinking / spatial visualization, 7 items measuring their teaching meteorology through computational thinking and practices, and 23 items measuring their epistemic cognition of teaching meteorology. All items in this survey use 6-point Likert type scale. The 23 items for measuring epistemic cognition consists of three subscales: epistemic cognition of teaching meteorology with traditional method (10 items); epistemic cognition of teaching meteorology with scientific practices (6 items); and epistemic cognition of teaching meteorology with computational thinking approach (7 items).

A. Results

We analyzed the 13 items measuring CT/SV and the 7 items measuring self-confidence in teaching meteorology with a Wilcoxon signed rank test. The results indicated that the CT/SV scores were significantly higher after the workshop (Table 1, RQ1). This indicates that the teachers personal CT/SV skills improved. The results indicated that self-confidence scores were also significantly higher after the workshop (Table 1, RQ2).

TABLE I. Survey Results For RQ1 and RQ2

RQ #	Pre-test MD	Post-test MD	*z*	*p*
1	4.18	5.00	3.06	.002
2	4.00	4.50	2.59	.010

Finally, we analyzed the teachers' responses to the three subscales (epistemic cognition of teaching meteorology with traditional method; epistemic cognition of teaching meteorology with scientific practices; and epistemic cognition of teaching meteorology with computational thinking approach) were analyzed using a Friedman rank-sum test because the assumptions of normality and sphericity were violated for the repeated measures analysis of variance (ANOVA).

For the pretest, the Friedman rank sum test result indicated a significant difference in the scores of the three subscales, $\chi^2(2) = 20.51$, $p < .001$. Three subsequent Wilcoxon signed rank tests were conducted for pairwise comparisons of the three subscale scores with a Bonferroni adjusted α level of .017. The results of the Wilcoxon signed rank tests indicate that scores of epistemic cognition of teaching meteorology with scientific practices and epistemic cognition of teaching meteorology with computational thinking approach were not significantly different but were both significantly higher than epistemic cognition of teaching meteorology with traditional method.

For the posttest, the Friedman rank sum test result indicated a significant difference in the scores of the three subscales, $\chi^2(2) = 21.75$, $p < .001$. Three subsequent Wilcoxon signed rank tests were conducted for pairwise comparisons of the three subscale scores with a Bonferroni adjusted α level of .017. The results of the Wilcoxon signed rank tests indicate that scores of epistemic cognition of teaching meteorology with scientific practices and epistemic cognition of teaching meteorology with computational thinking approach were not significantly different but were both significantly higher than scores of epistemic cognition of teaching meteorology with traditional method.

B. Conclusion

The data analysis results indicate that: (1) the summer workshop is effective in improving teachers' CT/SV skills and self-efficacy in teaching meteorology through computational thinking and practices; and (2) the summer workshop does not change teachers' epistemic cognition about how meteorology should be taught and teachers' preference for teaching meteorology with scientific practices and computational thinking approach over traditional method is evident both before and after workshop.

V. Project Status and Future Plans

We have completed two years of a project to innovate K-12 science education by creating a contextual framework to support the integration of computational thinking into primary and secondary education. The focus of the project is on providing the professional development that science teachers need in order to write lessons that motivate student learning of and practice with computational thinking. Current professional development includes guidance for computational thinking principles, instruction for downloading and analyzing real weather data, training for visualizing weather data in 3D using existing tools, and support for how to integrate computational thinking into K-12 classrooms. The result of our initial two years' work is a two-week training workshop that was taught in Summer 2021. Thus far, the teacher feedback has been positive and our initial surveys have indicated the workshops are effective at improving teachers' CT/SV skills and their self-efficacy in teaching meteorology through computational thinking and practices.

We are currently collecting data from teachers who are implementing our 3D Weather modules and teaching the associated CT and SV thinking skills in their classrooms in order to answer research questions related to how the teachers we trained are impacting their students' CT/SV skills. We are planning for an additional workshop in summer 2022, which will allow for another round of data collection for the workshop and student data collection during the upcoming school year.

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