Computational Thinking in Introductory Physics

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I. INTRODUCTION

“Computational thinking” (CT) is still a relatively new term in the lexicon of learning objectives and science standards. The term was coined in an essay by Wing [1] who said “To reading, writing and arithmetic, we should add computational thinking to every child’s analytical ability”. Agreeing with this premise, in 2013 the authors of the Next Generation Science Standards (NGSS) included “mathematical and computational thinking” as one of eight essential science and engineering practices that K-12 teachers should strive to develop in their students [2].

There is not yet widespread agreement on the precise definition or implementation of CT, and efforts to assess CT are still maturing, even as more states adopt K12 computer science standards [3]. In this article we will try to summarize what CT means for a typical introductory (i.e. high school or early college) physics class. This will include a discussion of the ways that instructors may already be incorporating elements of CT in their classes without knowing it.

Our intention in writing this article is to provide a helpful introduction to this topic for physics instructors, which is a very different goal than providing a rigorous survey of the literature. For more rigor, interested readers should consult Weintrop et al. [4], Sengupta et al. [5], and Grover & Pea [6].

We hope that our comments here will also be useful to the growing number of physics instructors who are integrating computer science (CS) into their classrooms through coding activities in VPython [7], JavaScript and other languages. Groups like PICUP and AAPT have a number of resources and workshops to facilitate this work [8, 9]. We ourselves lead an effort called the STEMcoding project which focuses on coding activities for high school and early college physics [10].

For brevity, in this article we will not discuss “unplugged” CT activities even though CT does not always require a computer, which is perhaps the first thing to appreciate about CT. This is because humans compute too!

II. DEFINING COMPUTATIONAL THINKING

One of the most highly cited papers on CT that is also relatively recent is Weintrop et al. [4]. Having noticed that experts were defining CT in different ways, Weintrop et al. went about identifying CT “practices” from the literature, from sample activities they collected, and from interviewing both teachers and STEM professionals on what kind of skills they associate with CT. Over half of the activities they sampled were on the subject of physics and their interviews included physics teachers and physics professionals.

The summary in their Fig. 2 concludes that there are four main CT practices, each with similar importance:

1. Data Practices – Collecting, Creating, Manipulating, Analyzing and Visualizing Data

2. Modeling and Simulation Practices – Using Computational Models to Understand a Concept, Using Computational Models to Find and Test Solutions; Assessing, Designing, and Constructing Computational Models

3. Computational Problem Solving Practices – Preparing Problems for Computational Solutions, Programming, Choosing Effective Computational Tools, Assessing different Approaches/Solutions to a Problem, Developing Modular Computational Solutions, Creating Computational Abstractions, Troubleshooting and Debugging

4. Systems Thinking – Investing a Complex System as a Whole, Understanding the Relationships within a System, Thinking in Levels, Communicating Information about a System, Defining Systems and Managing Complexity

Only one of the four CT practices – Computational Problem Solving – is what one might typically associate with coding, programming, or debugging. In this way, the CT practices of [4] reflect the idea that computational thinking does not necessarily require a computer.

Physics instructors looking over this list will recognize “Modeling and Simulation” as familiar practices they likely already use in their classrooms. For some time now simulations have been an important part of physics instruction through resources like PhET Interactive Simulations and Physlet Physics, as the paper acknowledges. Here the term “modeling” is used in much the same way that it is in the physics education community. Weintrop et al. [4] cites the NGSS, which was heavily influenced by the modeling movement and “modeling instruction” [11], as a primary reference for this category. The connection between CT and modeling is an important philosophical foundation for the “Bootstrap for physics” approach to integrating computer science into physics and physical science classrooms [12], which is a curriculum developed by the American Modeling Teachers Association.

Another CT practice is “Data Practices”. A more self-explanatory title for “Data Practices” might be “Working with
Data”. The list of activities associated with this practice has a great deal of overlap with the goals of a typical physics lab activity. This raises the possibility that CT may provide something useful to the current debate over the usefulness of physics labs ([13, 14]). We will return to this topic later.

The last CT practice is “Systems Thinking”, which is the most abstract of the four. For physics instructors, this practice can perhaps be understood as the skill of gaining insight from simulations designed to model situations that include multiple, complex interactions. Computation is valuable in physics because it allows the ideas of physics to be usefully applied to problems that are difficult to treat analytically. A classic example of this is numerically modeling air drag on a projectile or falling object. Although the only forces are air drag and gravity, from a student’s perspective this is a complex simulation with competing effects. A possible “systems thinking” activity would be to analyze the simulation to measure the terminal velocity and check if it agrees with the expectation from assuming balanced forces of drag and gravity.

Systems thinking can also involve understanding the connections between “micro” and “macro”. For example, typical physics courses talk about collisions between two objects before discussing fluid mechanics on the premise that fluid mechanics is simply the consequence of many objects colliding and interacting. So even this the most abstract CT practice seems to fit naturally within the learning objectives of a typical physics course.

III. THOUGHTS ON COMPUTATIONAL THINKING

It seems clear that CT (as characterized by [4]) makes many connections to physics teaching. But how should we assess CT? Arguably this is a question of what aspects of CT in particular should we focus on. As a physics instructor, a logical approach would be to de-emphasize the “Computational Problem Solving Practices” like “debugging”, “troubleshooting” and “programming” and focus on the other CT categories for the simple reason that our institutions are typically not valuing, in our opinion, by computer science initiatives that are primarily responding to the need to create a pipeline to fill software jobs.

In the next section we will provide some examples of differences between “math world” and “computer world”.

The connection to “sense-making” was suggested to us by Ruth Chabay who is well known for her work with VPython. Connecting CT with sense-making is helpful because it further helps to place CT into the realm of familiarity for physics instructors and, from an academic perspective, it creates a helpful bridge between CT and the literature on sense-making in physics (e.g. [15, 16]). As an illustration of the inherent relationship between sense-making and CT, last year we published a paper [10] describing an asteroids-like game we developed for the STEMcoding project. Through the course of modifying a simple 1D code for a ship thrusting around free space to a 2D code, there are numerous mistakes that students make that produce strange behavior in the game. Typical classroom examples are uncontrolled acceleration and forgetting to correctly update the position and velocity to allow the ship to move in the y-direction. Although we do not use the term in our paper, every step of identifying and correcting these errors engages the “sense making” skills of the student in addition to their computational skills.

The connection of CT to sense-making has another significance that relates to the careers students are pursuing. Introducing computation into high school or college non-major physics courses, in our opinion, should not be done solely to provide an early start to the kind of skills students would need as a professional physicist or as a software engineer. Relatively few of our students are on these career tracks. More often we are teaching students who are heading into traditional engineering careers. These students may never need advanced programming skills but many will go on to use sophisticated simulations to model any number of phenomena (e.g. stress and strain, heat flow, traffic patterns). For these students, physics-focused coding activities provide an introduction to the skill of making sense of what to them is a sophisticated simulation. This begins by showing students that even the most complex codes can be (and must be) tested for accuracy. We cannot let students assume that complex simulations are right because of their complexity. With this as an objective, we place an emphasis on code verification tasks and the student’s conceptual physics knowledge becomes an important tool for critical thinking and sense making about the program’s result. This emphasis is often undervalued, in our opinion, by computer science initiatives that are primarily responding to the need to create a pipeline to fill software jobs.

IV. CONCRETE EXAMPLES

As identified in the previous section, the translation from mathematical to computational representations is precarious
for students and instructors alike. In this section we provide concrete examples that could be used to assess this skill. Students are shown a sample of code with instructions to identify one or more problems without running this code.

A. Calculating Spring Force

In the “Planetoids with a Spring” activity from STEMcoding, the student considers an object attached to a horizontal spring. In the code they must calculate the spring force $F_{spring}$ and then on the following line use this (the only force) to calculate the change in velocity $\Delta V_x$ for an object during the time interval $dt$ for an object of mass $m$ at position $x$ given the relaxed length of the spring $L_{relaxed}$. The following code has been shown to produce an error:

$$F_{spring} = -k(x - L_{relaxed})$$
$$\Delta V_x = F_{spring}/mass \times dt$$

Identify the problem(s) with this code and how would you fix them?

As a mathematical representation, the code above looks fine, but it turns out that in most programming languages the above code will fail because of the lack of a * multiplier between the $k$ and the left parentheses on the first line. Without the * most languages will assume that $k$ is a function that is being passed the argument $x - L_{relaxed}$. This will fail because this function is not defined anywhere.

Arguably, there is also a potential order-of-operations problem with the second line of code. Most programming languages will divide $F_{spring}$ by $m$ before multiplying the product by the time interval $dt$, but conceivably some languages could multiply $m$ by $dt$ before dividing $F_{spring}$ by the result, giving the wrong numerical answer and with incorrect units. A safer, clearer way of writing that code would be like this:

$$\Delta V_x = (F_{spring}/mass) \times dt$$

This assessment connects more with “Computational Problem Solving Practices” like debugging and troubleshooting than it does with other CT practices. The next example is one that connects with a wider range of CT practices.

B. Perfectly Inelastic Collisions

In the “Planetoids with Momentum!” activity from the STEMcoding project [17] students take an asteroids-like code and modify it until the ship can collide and stick to a circle which is like a blob of goo drifting through space. In this way the activity illustrates a 2D perfectly inelastic collision.

There are detailed directions for this activity that includes the correct code to determine the final velocity of the ship and “blob” which in 1D looks like this:

```plaintext
if (collided == true) {
    vx1 = (mass1*vx1 + mass2*vx2)/(mass1 + mass2)
    vx2 = vx1
}
```

Students measure this final velocity and check that it matches with expectation from momentum conservation. Towards the end of this exercise, students are asked the following question:

The following code will give the wrong answer for the final velocity of the ship and blob after the collision:

```plaintext
if (collided == true) {
    vx1 = (mass1*vx1 + mass2*vx2)/(mass1 + mass2)
    vx2 = (mass1*vx1 + mass2*vx2)/(mass1 + mass2)
}
```
Copy this into your code, take out the expression you used before and run the code to see what happens. Why does this give a different (wrong) answer for the velocity after the collision?

This is an interesting example because the code looks effectively identical to the mathematical solution for two objects colliding and sticking together in a 1D perfectly elastic collision. But when the code is run, the student finds that instead of near-perfect agreement with the expectation from momentum conservation, the program may be off from the correct final velocity by tens of percent. To understand the reason for this, students must appreciate that \( v_{x1} \) is being updated and then the updated value of \( v_{x1} \) is used again in the following line of code. This is wrong because the mathematical expression only uses the velocity from before the impact to compute the velocity after.

This example illustrates a key difference between mathematical and computational representations is that the computer goes line-by-line through the program whereas there is really no equivalent to this in “math world” (i.e. high school or early college algebra). In general, students do not automatically look at a code and realize that the computer goes line-by-line or that the same code is run over and over again. Perhaps the first study of CT in introductory physics was by Aiken et al. [18] who found that high school students struggle to understand the iterative nature of the program.

The assessment just described also connects with “sense making” and code verification as discussed earlier. Importantly, it shows that even what appears to be a correct implementation of an equation needs to be verified for accuracy.

C. More ideas

If one considers the myriad things that can go wrong in translating from mathematical to computational representations, the task of developing ideas for CT assessments becomes much easier. It is not uncommon for CT assessments (e.g. [19]) to include at least one question where a sample code is shown (whether block based or text based) and students are asked to predict what will happen or what role a particular line of code is playing. Potential questions could range from relatively mundane issues like using \( ^\wedge \) in a language where it does not mean “to the power", to much more advanced questions like asking if a particular code will conserve energy [20].

V. THOUGHTS FOR THE FUTURE

Perhaps the most meaningful probe of CT is whether students can configure a code that they have used to model a new situation - i.e. in the real world. The emphasis there is needed because “Data Practices” is one of the key CT practices yet in our opinion (as a critique of both ourselves and other coding-in-physics initiatives) this is not a strength of the content and tools that are currently in use. A possible exception is Tracker Video which gives the user some tools to simulate the dynamics of objects in videos [21], but it does not have a fully featured coding interface.

To provide an example of what the future may hold Fig. 2 highlights a proof-of-concept where a direct measurement video of a fire extinguisher cart experiment (constant acceleration process). This framework can easily be adapted to allow students to model projectile motion, for example, with code from the angry birds exercise. Video credit: Interactive Video Vignettes.

FIG. 2. Screenshots at various times from a working demo (http://go.osu.edu/workingdemo) where our “accelerate the blob” code from the STEMcoding hour of code activity is run simultaneously with a direct measurement video of a fire extinguisher cart experiment. This framework can easily be adapted to allow students to model projectile motion, for example, with code from the angry birds exercise. Video credit: Interactive Video Vignettes.

Arguably “Data Practices” is the most important CT practice identified by [4] in that the paper mentions the word “data” over 100 times with only a few of these instances referring to student data, and it is the first CT practice discussed in depth there. Recently we pointed this out to David Weintrop and asked him if this was intentional. He said it was not, but he agreed that data practices is “at least as important” as the other CT practices.
Students need to configure a code to have the correct physics (constant acceleration) and they adjust the initial velocity and acceleration to match the motion on the screen. A link to the demo is available at http://go.osu.edu/workingdemo. It is not difficult to imagine similar activities for projectile motion or the “coffee filter” experiment where students model the motion of a falling object with air drag. There is some debate regarding the value of physics labs [13, 14] and activities of this kind may provide a useful new direction for research, especially now that an increasing number of smartphones and tablets can record slow motion video at 240 frames per second. This is the same frame rate that many of excellent direct measurement videos from Peter Bohacek were recorded [23].

VI. CONCLUSION

More and more states are creating or adopting K12 computer science standards [3], giving teachers more permission to integrate coding into physics courses than before. We hope this article provides helpful insights into the nature of CT, including ways that physics instruction already aligns with this instructional goal and ways that as a community we can work to help our students develop CT skills.

ACKNOWLEDGMENTS

We acknowledge support for the AIP Meggers Award and the OSU Connect & Collaborate grant program. We thank Ruth Chabay for insightful conversations and we thank the organizers of an NSF sponsored workshop on computational thinking that occurred May 2-5, 2019 in College Park, MD.

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