How computation can facilitate sensemaking about physics: A case study

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We present a case study featuring a first-year bio-science university student using computation to solve a radioactive decay problem and interpret the results. In a semi-structured cognitive interview, we use this case to examine the process of sensemaking in a computational science context. We observe the student entering the sensemaking process by inspecting and comparing computational outputs. She then makes several attempts to resolve the perceived inconsistency, foregrounding knowledge from different domains. The key to making sense of the model for this student proves to be thinking about how to implement a better model computationally. This demonstrates that integrating computation in physics activities may provide students with opportunities to engage in sensemaking and critical thinking. We finally discuss some implications for instruction.

I. INTRODUCTION

It is a well-known problem that students can progress through introductory physics courses, sometimes with good grades, and still lack understanding of the underlying principles, relations, and concepts. A common scenario is that students employ "plug and chug" strategies to manipulate mathematical formulae without engaging with the underlying physical principles. With this in mind, getting students to engage in sensemaking is crucial for achieving learning goals in critical thinking and understanding the physics itself [1].

Computation is important for students of physics to learn because it reflects current practices in the field, teaches important skills for research and other careers, and allows students to solve a greater number of more realistic problems [2]. Consequently, research-based efforts to sensibly integrate computation into the physics curriculum are well underway [3–5]. Therefore, we want to study to what extent computation provides a potential for students engaging in sensemaking, and under which conditions that potential may be fully realised.

We present evidence for sensemaking in the case of Sophia, a bio-science student who is interviewed while solving a physics problem on radioactive decay. Sophia uses both computational and non-computational arguments to make sense of the model. The process of modifying her program and comparing the outputs turns out to facilitate Sophia's sensemaking. We justify this claim by presenting evidence for how computation was helpful in the sensemaking process. Finally, we discuss implications for teaching and future research.

II. ANALYTICAL FRAMEWORK

The analytical framework for this study is founded on the following definition of sensemaking from [6], pp. 5-6: "A dynamic process of building or revising an explanation in order to [. . .] resolve a gap or inconsistency in one's understanding." While there have been numerous other attempts to define what sensemaking is, we chose this one because it unifies several aspects of sensemaking that others have highlighted: sensemaking as an epistemological frame, a cognitive process, and a discourse practice, all of which are relevant to this project.

The process of sensemaking involves (a) realising that there is a gap or contradiction in one's knowledge, (b) iteratively proposing ideas and attempting to connect them to existing knowledge or other ideas, and (c) evaluating that these ideas are consistent and do not lead to additional contradictions [6]. In this paper, we will use this definition to study how computational activities may provide opportunities for sensemaking in interdisciplinary science problems.

III. METHODS

The case comes from a pilot study conducted with first-year bio-science students at a large research-intensive university in Norway. These students learned computation integrated with biology in the previous semester and were following a physics course in the semester when this study took place. The physics course had not yet covered radioactive decay by the time we interviewed the students. We targeted students with a wide range of self-reported programming expertise who were also comfortable thinking aloud.

Subsequently, we performed a series of semi-structured cognitive interviews in Norwegian where students worked on the task alone. The interviews borrowed heavily from think-aloud protocols, but students could ask for help with syntax should they need it, provided they were able to articulate what they wanted the code we gave them to do.

Follow-up questions on students' reasoning were asked by the interviewer on various occasions, interspersed throughout the think-aloud segments. This tends to change the students' thought processes, often improving the results. Protocols obtained in this way tend to be more valid than the ones were students recall their reasoning after the fact, however [7].

We gave the interviewees a toy model starting off with 1000 radioactive nuclei and told them that 10% of the remaining nuclei would decay every month. The students first calculated the remaining number of nuclei for the first two months (where the answers were still integers) by hand. The next step for the students was to reproduce these answers by writing a Python program in Jupyter Notebook. This is the familiar programming environment they used throughout the previous semester. Finally, they were asked to extend the calculations to 60 and 100 months and (if time allowed) plot the results.

This task was specifically designed to allow students to discover a perceived trade-off between accuracy and realism that would require sensemaking to resolve. After a while, you need several decimal points to mathematically describe 10% of what remains, yet when counting nuclei, in general one expects the numbers to be integers. While the toy model we provided may be approximately correct for a large number of nuclei, at lower amounts one would have to interpret the output as an average across many identically prepared experiments for the numbers to make sense.

All the students interviewed (N=5) at some point considered rounding the answers to the closest integer to avoid working with fractions of nuclei, although some did this only in response to follow-up questions from the interviewer. Every student also expressed some concern about the mathematical accuracy of their results when rounding the numbers in this way. Two of the interviewees made some progress toward resolving this contradiction by interpreting the un-rounded numbers as an average, one of which was Sophia.

The typical length of an interview was about one hour. All interviews were recorded on audio and video, both of the student and the computer screen. Subsequently, the transcripts were translated from Norwegian into English. We analysed the transcripts using the definition in [6] and looked for the following: The student (a) realising she cannot fully explain the physical phenomenon she is modelling or aspects of the model itself, (b) proposing explanations and trying to connect them to scientific or everyday knowledge and (c) evaluating these explanations to ensure consistency.

We then looked at what the student was doing with computation inside and outside of these sensemaking episodes, and asked the following questions: What happens in this computational context when the student engages in sensemaking? Is the computational aspect of the task a help or hindrance to this process?

The case we present illustrates how sensemaking may happen in a computational context. While not the most typical case for this group of students, Sophia's interview was chosen for analysis because her sensemaking was rather explicit in the transcript. Additionally, she ended up using language that was clearly computational to make a profound argument about how to model the physical phenomenon and interpret the results.

IV. COMPUTATIONAL SENSEMAKING CASE

"Sophia" (pseudonym) is a Norwegian student in her mid-20s, a few years older than most students taking first-year university courses. She describes her experience with programming as one of a fair degree of mastery in most cases. Compared to the average student in the programming course for bio-science students, she comes across as more confident and relaxed than most when working with computer code. During the interview, she rarely asked for confirmation that she was on the right track, and she did not hesitate long before trying something out.

We begin our analysis at the point where Sophia has set up her program to calculate the number of remaining nuclei for the first three months: 1000, 900.0 and 810.0, respectively.

> **Sophia [14:35]** *There. Now it's right. [But] now I might want to round these* [indicates 900.0 and 810.0] *to get… well, just whole numbers.*

She implements this rounding to the closest integer when displaying the output from the program, but not in the actual calculations, and checks that it works.

> **Interviewer [15:05]** *Could you tell me a little more about why you would want to round them?*
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> **Sophia** *Because these are atoms, and you sort of can't have half… or I don't know… it seems a little unnecessary to include, like, 810.0 atoms, in a way.*

We interpret *"you sort of can't have half…"* as that you cannot have a fraction of a nucleus and still call it a nucleus of that particular element, which is a point Sophia returns to later on.

At this point, we have reached the start of the sensemaking process. It is divided into three separate segments that correspond to the three ideas Sophia proposes to make physical sense of the numbers given to her by her program.

A. Sensemaking segment I

Sophia moves on to the next part of the task, modifying her program to repeat calculations all the way up to 60 months. She inspects the output and indicates the last ten months in the sequence, with 3, 3, 3, 2, 2, 2, 2, 2, 1, and 1 nucleus, respectively.

> **Sophia [16:30]** *This looks a little strange… Because here there are no decimals. So… here I'd include the decimals because, like… you can't take 10 percent of… or, I get that you get, like, the same number several months in a row.* [indicates the earlier sequence 6, 6, 5, 5] *Because 10 percent of 6 is still above 5, like. I'm going to include the decimals.*

While cutting the decimals for large numbers seems fine to her, Sophia realises that for smaller numbers there is something she needs to find an explanation for. Why does the number of nuclei remain constant for several time steps and then changes more than 10% rather abruptly? In terms of our sensemaking framework, the sensemaking process thus starts in reaction to the computational output when she realises that something is *"a little strange"*.

Using computation also allows her to include the decimals and test this change, which she immediately does. Yet, in terms of our framework, the idea that Sophia proposes here is first and foremost mathematical. She talks about numbers in a sequence, decimals and percentages, but this discussion stands on its own removed from the physics and computational contexts it occurred in.

B. Sensemaking segment II

After resolving some bugs (one syntax error and a few logical errors), Sophia sees the un-rounded numbers for all 60 months. After verifying that they seem to be the correct numbers mathematically, she is told that she is free to move on to the next task. Despite this suggestion, she decides she would rather continue making sense of the model.

> **Sophia [20:18]** *Umm, yes. Right now, I'm thinking – I just have to say it, because right now I am a little unsure about… because there are now so many decimals and…* [indicates the final months with 2.21…, 1.99… and 1.79… nuclei] *because one atom can't… you can't take 10 percent of one atom, like. So, this becomes sort of random whether, in a way… whether it splits or, like, if it loses one atom to radioactivity or not. So, I'm really not entirely happy with these numbers. But I can move on to the next one, I guess.*

We interpret this as Sophia revisiting her earlier statement: Can you have a fraction of a nucleus? The outstanding feature of this segment is the critique of her previous choice, which according to our framework is indicative of sensemaking going on.

Initially, Sophia seems hesitant to exit the sensemaking process prematurely, and she may be experiencing some friction between the sensemaking and how she frames the interview situation. The initial "*I just have to say it*" at 20:18 seems to indicate that at that point she was about to engage in an activity she considered not wholly appropriate for the way she was framing the activity at the time [8].

One should also note that in contrast to the previous sensemaking attempt, this one foregrounds the ideas from physics (atoms, radioactivity) with a nod to the mathematics embedded in them (percentages, randomness).

C. Sensemaking segment III

At this point the interviewer intervenes and invites Sophia to discuss a little more why she is not happy with the numbers, in effect sustaining the sensemaking frame. Initially this invitation is met with minor resistance, possibly because it was suggested she move on in segment II. Sophia states that she does not want to spend so much time and energy thinking about an open-ended task which is not clear about what it wants from her, so she is *"choosing the easy way out"*. After being asked what she would do if she were a scientist and this was an important result to her, Sophia resumes the sensemaking process:

> **Sophia [23:20]** *So, already after the third month here, then I would have taken, like,* [indicates month 4 with 656.1 nuclei] *here it reads point 1 – then I might have put in a* for *loop with* choice? *I think it is* [random.choice()[1]] *you use. Whether or not, like, that one… like, whether the decimal, whether that is a whole atom that goes away or not. So, in a way it becomes a sort of choice… thing. Such that when you run it as a model for the first time, then maybe… yes. Then maybe all… eh, the radioactive atoms are spent after, like, 56 months… and then the next time they are spent after 60 months. And the time after that maybe after 70 months. Eh, and then I would… yes, then I would have made a program or maybe a* def-*function and then run that many times and look at, percentage-wise, then, how probable is it that, eh, all the atoms… yeah, are gone after 50 months or after 70 months. So, I'd rather make that kind of model, because… eh, you kind of can't make this* [indicates the output] *completely accurate... But at the same time, when I think about it, it is… the probability of when that is going to happen is a little present in these numbers, too.*

At this point Sophia is using *computation* as a tool for sensemaking, something that was not explicitly evident in her earlier attempts. The mathematics and physics are still present in the background. Referring back to our framework once again, Sophia did mention randomness in segment II, yet this is the first time she proposes to interpret each un-rounded number as an average. But critiquing that idea leads to the question: an average of what? Of different *simulations. "I would have made a program* […] *and then run that many times and look at, percentage-wise, then, how probable is it that* […] *all the atoms* […] *are gone after 50 months or after 70 months."* We claim that this point, firmly embedded in the computational nature of the task, is key for Sophia's bridging the gap in her understanding she has been wrestling with.

As opposed to the simplified difference equation she was working with originally, the approach suggested here incorporates randomness: two sets of 1000 nuclei would not necessarily decay in identical ways. This realisation does not

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[1] https://docs.python.org/3/library/random.html#random.choice

mean she has a complete idea of how to implement it computationally, but sensemaking is about how you get there.

In summary, we have identified three sensemaking segments, in which Sophia foregrounds knowledge from the following domains:

- Segment I: Mathematics
- Segment II: Physics
- Segment III: Computation

These segments together clearly demonstrate the sensemaking process: Sophia (a) realises that rounding the numbers hides information. It seems inaccurate that the number of nuclei appears unchanged for several time steps and then abruptly changes significantly more than 10%. But *not* rounding the numbers leads to working with fractions of a nucleus, which conflicts with her intuition about how the world works, as established prior to segment I. In each segment Sophia (b) iterates by proposing ideas and (c) critiquing these to make sure they are consistent in themselves and with other ideas.

The sensemaking process ends with the resolution of changing the interpretation of the numbers in the toy model. Instead of the actual number of nuclei in one experiment they represent an average across an ensemble of computational simulations. At this point, we interpret Sophia's statements to mean that she regards both integers and decimal numbers as valid outputs from her program. She has also attained a rough idea of how to implement the simulations in question.

V. DISCUSSION AND CONCLUSIONS

In this paper, we have shown that computation helped Sophia in two ways. First, she was able to modify her program back and forth between rounding and no rounding with relative ease. In the first two sensemaking segments, inspecting and comparing the outputs of these approaches provides an entry point into the sensemaking process: *"This looks a little strange…"*

Second, we argue that the key to Sophia's interpretation of her output as an average is to think computationally about the problem, which is what happens in segment III. When discussing how to implement a more realistic model computationally, she realises that her current results can be interpreted as an average of several such simulations: *"The probability of when that is going to happen is a little present in these numbers, too."*

Without claiming that this case is common or representative for this group of students, we argue that this case study provides an existence proof that computation can provide fertile ground for student engaging in sensemaking. Specifically, working computationally allowed Sophia to (a) realise a gap in her understanding, (b) implement ideas and (c) test and critique the results for consistency. We observed that in this context, the idea that drew most heavily on computational knowledge proved the most fruitful in the sensemaking process.

To determine under which circumstances this potential for sensemaking can be fulfilled, further research is needed. In the other four interviews, we did note other examples of students beginning to engage in sensemaking in response to the output of their programs. What is special about Sophia's case was the way her computational resources helped her make sense of the apparent contradiction between the physics (realism) and mathematics (accuracy) in the model. She also initially ignored the interviewer's suggestion to move on at the start of segment II. It remains to investigate how this would play out in a classroom setting, where there is no interviewer to help sustain the sensemaking process like at the start of segment III. Video observations is one possible way to probe this.

Future studies could also identify the thresholds for entering and successfully resolving a sensemaking process, respectively, using computation. This would have profound implications for how instructors integrate computation in science classes, for instance when designing tasks that go beyond procedural use of computer programming as a tool. If critical thinking is important to us, we should attempt to realise the full sensemaking potential in computational activities. It is then necessary to ensure that our students have sufficiently strong computational foundations to engage in these sensemaking tasks.

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