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 setting, we build on previous work on sensemaking by studying the process in a computational science context. We observe the student using computation as an entry point into the sensemaking process and then making several attempts to resolve the perceived inconsistency, drawing on knowledge from several domains. The key to making sense of the model for this student proves to be thinking about how to implement a better model computationally. We demonstrate that integrating computation in physics activities may provide students with opportunities to engage in sensemaking and critical thinking and discuss some implications for instruction.

I. INTRODUCTION

It is a well-known conundrum that students can progress through introductory physics courses, sometimes with good grades, and still lack understanding of the underlying principles, relations, and concepts. A dreaded, but common scenario is students employing “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]. As a consequence, research-based efforts to sensibly integrate computation into the physics curriculum are well underway [3]. Therefore, we want to study to what extent computation provides a potential for students engaging in sensemaking, and under what 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 she is working with. We claim that because Sophia can easily modify her program and compare the corresponding outputs, sensemaking is facilitated. We justify this claim by presenting evidence for how computation was helpful in Sophia’s 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 [4], 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 since 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 [4]. 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. While this tends to change the students’ thought processes, so they generally do somewhat better, protocols obtained in this way tend to be more valid than the ones were students recall their reasoning after the fact [5].

We gave the interviewees a toy model starting off with 1000 radioactive nuclei and told them that 10% of the re-
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. We then had them reproduce these answers by writing a Python program in Jupyter Notebook, 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 amount of 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 [4] 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.

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’d round them?

**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. We divide it 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**

She 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 else she needs to find an explanation for: The number of nuclei remaining constant for several time steps and then changing more than 10% rather abruptly. The sensemaking process thus starts as a reaction to the computational output.

Using computation also allows her to implement and test this change, which she immediately does. Yet, the argument Sophia makes here is purely 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 numerical errors), Sophia sees the un-rounded numbers for all 60 months, in effect sustaining the sensemaking frame. Initially to discuss a little more why she’s not happy with the numbers in a sequence, decimals and percentages, but this discussion stands on its own removed from the physics and computational contexts it occurred in.

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? This segment shows a lot of critique of her previous choice, which is indicative of sensemaking going on.

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 [6].

We also note that in contrast to the previous sensemaking attempt, this one contains mainly physics ideas (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’s not happy with the numbers, in effect sustaining the sensemaking frame. Initially this invitation is met with minor resistance. Sophia states that she doesn’t want to spend so much time and energy thinking about an open-ended task that isn’t clear about what it wants from her, so she’s “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 absent in her earlier attempts. The mathematics and physics are still present in her argument. Sophia did mention randomness in segment II, but only here is she interpreting the un-rounded numbers as an average. But that begs 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 mean she has a complete idea of how to implement it computationally, but sensemaking is about how you get there.

¹ https://docs.python.org/3/library/random.html#random.choice
In summary, we have identified three sensemaking segments, where Sophia draws on knowledge from the following domains:

- Segment I: Mathematics
- Segment II: Physics (mathematics)
- Segment III: Computation (physics, mathematics)

These three 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 Sophia 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 is her 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.”

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. 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 in Sophia’s case.

Future studies could compare 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. 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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