IDENTIFYING AND DEFINING THE COMPUTATIONAL PRACTICES OF INTRODUCTORY PHYSICS

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ABSTRACT

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Computation is an important skill that is used in almost all modern scientific investigations. For this reason, the task of educating the population on the use of computation in engineering is of primary interest to many professionals – from industry to academia. Although there has been much prior research on computation in education broadly, prior research within the particular sub-discipline of introductory physics still has many unanswered questions that must be addressed. At the forefront of these unanswered questions, there is increasing interest in the various computational practices that students engage in and the types of thinking that accompany them. Accordingly, this thesis attempts to deepen the understanding of computation by identifying and defining the computational practices that are indicative of computational thinking that introductory physics students frequently engage in.

First, we identified the common, less common, and unobserved computational practices in a novel physics classroom – Projects and Practices in Physics (P^3) – by using a theoretical framework and two qualitative methodologies. Identifying the broad and sometimes vague computational practices defined by the theoretical framework was facilitated by both a task and a thematic analysis applied to in-class video data.

Next, we defined those practices in concrete terms relative to the course from which data was collected. Each practice has a set of characteristics, and each characteristic has a set of qualities that can be defined in terms of the physical concepts that students must grapple

with in this and related courses.

Finally, we provide discussion on the possible lines of reasoning behind a given practice's frequency. Many of the learning goals that the course was designed around inevitably influenced the types of frequencies of the practices that we identified.

Answering these types of questions is of importance to anyone interested in integrating computation into the undergraduate physics curriculum. A better understanding of the different computational practices that students engage in can only help to mitigate the many challenges associated with teaching computation. Accordingly, this thesis is meant to shed light on the computational practices that students frequently engage in while solving introductory physics and engineering problems.

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Chapter 1

Introduction

Since the advent of relatively inexpensive and powerful computers, researchers have been interested in their use as both professional and pedagogical tools. Their ability to quickly and precisely perform extremely large amounts of numerical calculations makes them well suited for modeling and solving modern problems in the STEM fields (e.g., engineering or biostatistics). Similarly, their ability to easily generate realistic visualizations makes them well suited for the communication of scientific information. For these reasons, computation is indispensable in modern scientific pursuits and has increasingly been the focus of education research [1, 2].

Computation, or the use of computers to analyze complicated systems, continues to grow in many fields. Given its utility in these types of professional domains, the task of effectively training students in computation has risen to the forefront of STEM education research. However, this important task has been shown to involve challenges, as there are varied skills and pieces of knowledge that students must develop a mastery of in order to effectively utilize computation. Still, the desire to integrate computation into the STEM curriculum is stronger than ever [3].

While using computation to solve complex physics and engineering problems, practitioners often engage in what are called computational practices. Computational practices can be defined, in one way, as a synthesis of computational knowledge and computational skill – highlighting the importance of being able to put theoretical ideas to practical work [4]. Although knowledge and skill alone are important, being able to combine the two into an effective practice is even more so. Although attempts have been made to define computational practices broadly [4, 5, 6, 7], they are still lacking clear and precise definition within many particular domains (e.g., computational physics). Accordingly, this thesis focuses on identifying the common computational physics practices that students engage in while solving realistic physics and engineering problems in an introductory mechanics course for engineering students.

Computational practices can be defined, in another way, as the things that students will actually be doing when they have graduated and, presumably, get a job in the field. These practices are probably discipline specific (e.g., physics may have different practices than biologists) and industry specific (e.g., manufacturing materials probably has difference practices than testing materials).

There are a number of reasons for focusing on computational physics and its associated computational practices. Perhaps most important is that there is a high demand for computational skills in the workplace for recent physics graduates [4]. With many students entering school for future job prospects, being able to effectively prepare future graduates for entering industry or continuing education requires in-depth research to develop best practices. As documented in a recent report from the AIP, there is high demand for computational skills in the workplace for recent physics degree holders – things like programming, simulating, or modeling [8]. Modern physics curricula should reflect the modern practices of professional physicists, and computation is now seen to be just as important as theory and experiment. For this reason, faculty from physics departments across the nation call for more computation in the curriculum [3].

Perhaps most important, computational skills are becoming increasingly necessary 21st century skills, especially for anyone using physics. With most theory on solid foundation, computation can be used to apply it to complex, non-linear, and realistic modern engineering problems.

Additionally, it is believed that students of computational physics gain a deeper understanding of the physical concepts [9, 10] along the way. Visual packages such as VPython or Glowscript [11] allow novice programmers to create three-dimensional visualizations that allow them to more easily interact with the fundamental concepts.

Further, computation allows for the analysis of realistic problems that have no closed-form solution. Its ability to numerically integrate supports a more exploratory approach to analyzing physical systems and learning physics. That is, the repeated application of Newton's second law allows for a more general analysis. This more exploratory approach is thought to encourage students to construct more realistic and accurate (e.g., including air resistance) computational models through computational thinking [4].

Computational thinking is a term that has become increasingly popular since its introduction in the early 1980s [12, 13, 14, 15]. This term, although frequently used today, is difficult to concisely explain given its many and varied definitions. Even within the fields of education and computer science, many different viewpoints exist on the topic, and the corresponding definitions are just as varied [16]. However, many of these definitions share one fundamental characteristic: solving complex problems through abstraction and analytic thinking with the aid of computer algorithms. In other words, this type of thinking is any type of thinking that focuses on using computer algorithms to solve problems. This type of thinking is extremely important in engineering, where differential equations are solved numerically to solve problems. Accordingly, computational thinking focuses on the use of computer algorithms.

This type of thinking is so highly valued by the modern enterprise of science education that the Next Generation Science Standards (NGSS) includes elements of computational thinking in K-12 settings. As early as the fifth grade, students are expected to be able to think computationally. The NGSS describes computational thinking, at this level, in terms of analyzing data and comparing approaches. By the time students reach middle school, computational thinking advances to analyzing large data sets and generating explanations. Finally, in high school, computational thinking expands to constructing computational models and using them to answer questions [5]. Clearly, computational thinking is a complicated concept which requires substantial explanation.

Experts in the field still have a ways to go when it comes to clearly defining computational thinking within science education, and within physics education more specifically. However defined, though, this type of abstract and algorithmic thinking is pervasive – it extends beyond computer science into fields from geology to astronomy, and even beyond STEM [2]. It is becoming increasingly clear that "computational thinking is a fundamental skill for everyone, not just computer scientists [13]."

Given recent interest in scientific practices, and computational thinking more specifically, a taxonomy of the computational practices indicative of computational thinking has been proposed be Weintrop et. al [7]. This taxonomy, comprised of twenty-two individual yet inter-related practices, fitting into four different categories, is meant to help guide instructors and researchers as they attempt to teach and better understand computational thinking in science classrooms. Each practice, according to the taxonomy, is defined broadly and from an expert level so as to be applicable to a wide range of science classrooms.

However, the broad and expert-generated definitions that make the taxonomy widely applicable also leave it relatively vague and difficult to apply to any particular situation. Reducing the vagueness and difficulty of applying this taxonomy to a specific domain of inquiry (i.e., introductory physics) is a challenging but important task. Having a taxonomy that is both precise and easy to apply will provide a solid foundation for instructors to generate/validate computational problems and for researchers to analyze the learning process. Accordingly, this thesis attempts to answer the following questions:

1. what are the computational practices common to introductory mechanics,

2. how are those practices defined in terms of concrete examples, and

3. why do we see those practices?

It cannot be overstated that it is the culture of P^3 – the active and social engagement of students in learning that is encouraged through continual tutor interaction – that influences the practices that we see in our data heavily.

Ultimately, this thesis is meant to illustrate the process of identifying the common practices that groups of students engage in while solving a realistic computational introductory physics problem. In Ch. 2 we explicate the prior research on computation and its results, as well as the theoretical and methodological underpinnings of the study. This includes the historical and more recent results from Physics Education Research (PER) and Computer Science Education Research (CSER). In Ch. 3, we describe the course from which our data has been collected – a calculus-based introductory physics course with a focus on engineering, working in groups, and computation. We also describe the types of computational problems students are working on while in class. In Ch. 4, we provide a motivation for not only the existence of the study, but also the theories and methods that we decided on using. Finally, in Chs. 5–7, we present the analysis and results of our current study with discussion and concluding remarks.

Chapter 2

Background

In order to better understand the analysis and results of this thesis, there are three broad and underlying topics that deserve elaboration. First, the concept of computational thinking and its definition. Next, the results from Physics Education Research (PER), including the various implementations of computational physics and its effect on learning. Finally, the qualitative methodologies and the framework that we have used to guide our analysis.

2.1 Computational thinking

As mentioned in the introduction, computational thinking and its associated practices within introductory physics are of primary interest to this thesis. These practices are the observables that we can look for within our data. Building on previous research that focuses on scientific practices [4, 5, 7], we have attempted to more clearly and precisely define the computational practices within introductory physics.

The history of computational thinking and its definition is long but incomplete [12, 17, 13, 14, 15, 16, 2]. The term was first introduced by Seymour Papert as it related to students actively constructing knowledge through the production of an artifact – ideally, but not necessarily, a computer program. This idea of learning through construction, often called "constructionism," was built on the Piagetian idea of "constructivism." Constructivism states that students learn best when they are actively involved in the construction of their knowledge [18]. Constructionism, on the other hand, believes that it is the construction of a tangible object that is of critical importance when actively constructing knowledge [12].

Papert was very interested in looking at how computers could be used to teach. Some of his earliest research into an educational programming language (i.e., Logo, aptly named for its focus on reasoning) and its use as a learning tool focused heavily on the construction of two-dimensional shapes on a computer screen [19]. However, Papert did not initially attempt to define computational thinking in terms of constructionism. Rather, he commented that attempts to integrate computational thinking into everyday life had failed because of the insufficient definition of computational thinking. He optimistically claimed that more attempts to define computational thinking would be made, and eventually "the pieces will come together [12]." Papert would later go on to say that computational thinking involves "forging new ideas" that are both "accessible and powerful [17]."

More recently, building on Papert's preliminary observations, Jeanette Wing defined computational thinking as it related to the processing power of modern computers with the addition of human creativity. This echoed the core sentiments expressed by Papert of using human creativity to "forge new ideas" that are "computationally powerful". She states that "computational thinking involves solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science. [13]"

Wing was careful to remind readers that computational thinking is a fundamental skill for everyone, not just computer scientists [14]. This speaks to the robust nature of computational thinking, but also speaks to the difficulty in clearly defining it. She believed that computational thinking should be taught at the introductory college level, and should even go so far back as to be introduced at the pre-college level. Wing made substantial progress in defining computational thinking, but still falls short – especially within particular subdomains like computational physics or chemistry.

Further elaboration by Alfred Aho pointed out that the process of finding the right tool (e.g., a software package like Excel or a model like the Euler-Cromer algorithms) for the right job is a clear indicator of computational thinking. He considered computational thinking to be the "thought processes involved in formulating problems so their solutions can be represented as computational steps and algorithms." Mathematical abstraction is at the heart of computational thinking, and being able to choose between competing abstractions is of critical importance [15]. Aho made clear that although there are many useful definitions of computational thinking within the field of computer science, new domains of investigation (e.g., introductory physics) require definitions of their own. It is important to have these domain-specific definitions to better encourage the associated practices.

Theoretical definitions aside, The Next Generation Science Standards has most recently attempted to operationalize a definition of computational thinking in K-12 science classrooms. They have included computational thinking as one of their core practices, and identify a handful of expectations for K-12 students that require computational thinking. According to the NGSS, students should be able to [5]:

E1. Recognize dimensional quantities and use appropriate units in scientific application of mathematical formulas and graphs.

E2. Express relationships and quantities in appropriate mathematical or algorithmic forms for scientific modeling and investigations.

E3. Recognize that computer simulations are built on mathematical models that incorporate underlying assumptions about the phenomena or system being studied.

E4. Use simple test cases of mathematical expressions, computer programs, or simulations to check for validity.

E5. Use grade-level-appropriate understanding of mathematics and statistics in analyzing data.

These expectations, though useful, are still rather broad and can be reasonably applied to any science classroom. For example, the expectation of being able to recognize dimensions in a mathematical formula (E1) might show up in a chemistry classroom focusing on mass conservation before and after a chemical reaction. Alternatively, the expectation of students understanding that simulations rely on mathematical models (E3) might show up in a biology course involving predator/prey predictions based on an underlying computational algorithm (e.g., the Lotka-Volterra equations).

More clearly and precisely defining these expectations is an important task, especially within a particular domain of interest. Without precise and domain-specific definitions, applying them to a particular classroom is rather difficult for practitioners. Accordingly, one field whose precise definitions are particularly lacking (though, progress is being made on) is physics.

Similarly, although defining computational thinking within K-12 is an ideal starting point, it should also be extended to more advanced levels. There are many concepts requiring computational thinking that are unique to the university level and above, and as students advance throughout their educational career, it is important that we study them. To wit, the AAPT Recommendations for Computational Physics in the Undergraduate Physics Curriculum has identified the skills (physics-related and technical) and tools that should be included in a modern physics curriculum [4]. These recommendations include roughly ten skills like debugging, testing, and validating code and tools like Excel or Python.

Still, more research is needed to not only more clearly define the computational practices observed in introductory physics, but also to more clearly understand the habits of mind and types of thinking that students are engaging in. It is important that we further define expectations around computational thinking within a particular domain of interest (i.e., introductory physics) and at a particular level (i.e., university calculus-based).

2.2 Physics Education Research

This section focuses on the development of the different implementations of computational physics problems (e.g., BOXER) [20, 21, 3, 22], the results from PER (e.g., student challenges) [9, 23, 24, 25, 26, 27], and most importantly the remaining questions.

2.2.1 Implementation

The focus on computational thinking in Physics Education Research (PER) has been increasing over the past decade. Historically, computation as a pedagogical tool has taken many forms, but its implementation has usually focused on two things: its ability to handle tedious calculations and its ability to generate precise visualizations.

For example, one of the earliest forms of computation at the introductory level, called BOXER, used "simple programming" to generate two-dimensional shapes on a computer screen [20]. This "reconstructible medium" allowed even novice programmers to take advantage of the processing and visualization power of computers. To illustrate, Fig. 2.1 shows the graphical user interface for a program in BOXER that is meant to generate a star and a triangle for two different objects. The underlying algorithms are laid out in sequential steps that repeat a specified number of times.

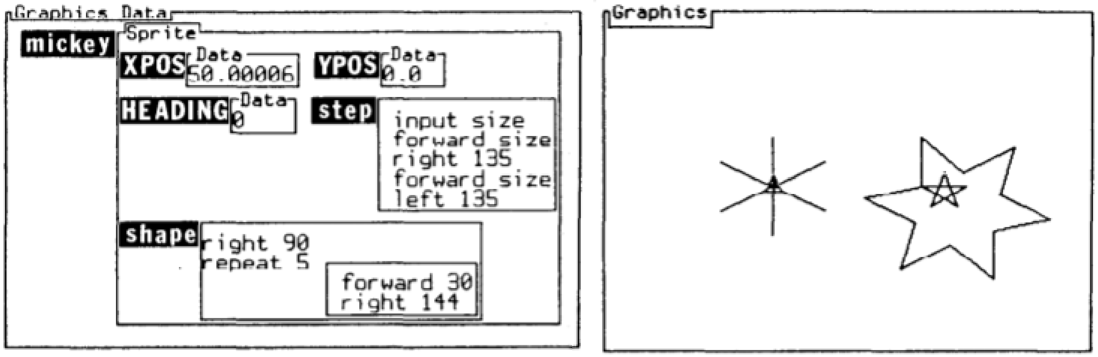


Figure 2.1: Graphical user interface for BOXER showing the graphics data (e.g., the step instructions) and the resulting graphic for a sprite named "mickey."

A more recent implementation of computation takes the name VPython: the Python programming language with the Visual module. Historically, the goal of developing VPython was to "make it feasible for novice programmers in a physics course to do computer modeling with 3-dimensional visualizations [11]." The current version of VPython does just that. Although VPython was ideal for novice programmers, it also catered to more advanced users. Its underlying algorithm is an Euler-Cromer style integration to calculate the constantly updating position and momentum (or velocity) of an object within a while loop that depends on time. For example, Fig. 2.2 shows the basic structure of a very simple but powerful program. This Euler-Cromer algorithm can be used to analyze rudimentary situations (e.g., free-fall motion) as well as more complicated and realistic (e.g., the motion of satellites and rockets).

Along with the development of VPython, a software called Easy Java Simulations (EJS) was increasing in use [28]. These simulations were meant to give students a little more control behind the scenes, similar to VPython, while still limiting the generalizability like PhET simulations (described below). For example, a simulation of a pendulum could be constructed in EJS by dragging a particular object (e.g, a pendulum bob) into the model

```
1  bead = sphere(pos=vector(0,0,0), radius=0.1, color=color.red)
2
3  bead.m = 0
4  bead.q = 0
5  bead.v = vector(0,1,0)
6
7  g = vector(0,9.81,0)
8  E = vector(0,0,0)
9
10 Fg = -bead.m*g
11 FE = vector(0,0,0)
12
13 Fnet = Fg + FE
14
15 bead.a = Fnet/bead.m
16
17 t = 0
18 tf = 10
19 dt = 0.01
20
21 while t < tf:
22     rate(100)
23
24     bead.pos = bead.pos + bead.v*dt
25     bead.v = bead.v + bead.a*dt
26
27     t = t + dt
```

Figure 2.2: A program illustrating that the basic control structure and integration algorithm are pre-written so that students can focus on the computational force model that must be constructed in line 11.

and using their built-in editor to solve the associated differential equation (see Fig. 2.3). Only a small amount of modification is needed, reducing the load on novice programmers – something shared with the VPython programs of PER [29].

Another implementation of computation, frequently used today, are the Physics Education Technology (PhET) simulations [30]. These simulations have realistic graphics that display buttons, sliders, and knobs that can be graphically tweaked to change parameters in a system. This type of testing – searching for the effect on a physical system with the variation in a parameter – is meant to be more engaging and conducive to learning. For example, the PhET simulation shown in Fig. 2.4 is meant to demonstrate the dependence of a pendulum's motion (e.g., its period or amplitude of oscillation) on the various parameters of the system (e.g., the length of the pendulum or the magnitude of friction). Being able to

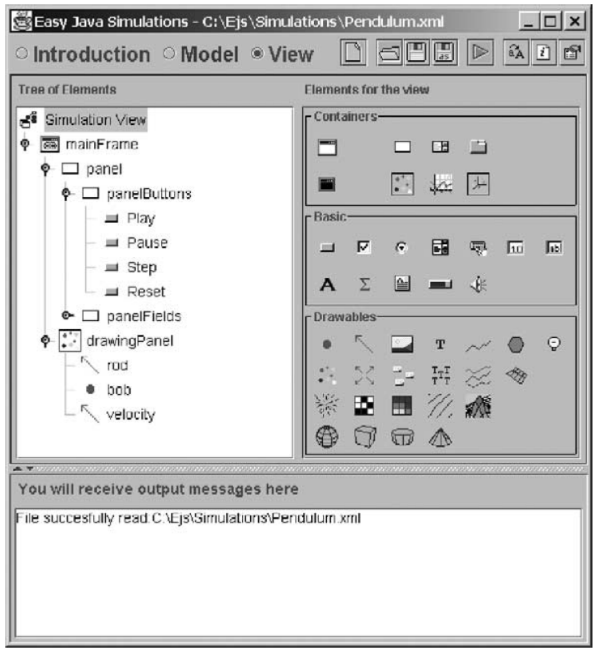


Figure 2.3: Graphical user interface for an EJS illustrating the “drag-and-drop” nature of the software. Elements (e.g., a pendulum bob) can be added or removed from the different panels (e.g., the drawing panel) in the simulation view.

hold one parameter constant while varying the other helps students to confidently identify its qualitative effect.

Finally, one of the most recent implementations of computation at the introductory level is called Glowscript [9]. Glowscript is an on-line Integrated Development Environment (IDE) using VPython which is designed, in part, to easily generate three-dimensional visualizations. For example, the rather complicated Glowscript program shown in Fig. 2.5 uses an inverse-square electric field model with “for” and “if” loops to generate a visual representation of the electric vector field at any point in space surrounding a discrete charge distribution.

This more realistic and descriptive three-dimensional visualization leveraged by Glowscript and VPython is thought to encourage students to form a deeper understanding of the underlying physics concepts. Although many different implementations of computation exist [19, 20, 30, 9], research focusing on improving those implementations in PER is still lacking.

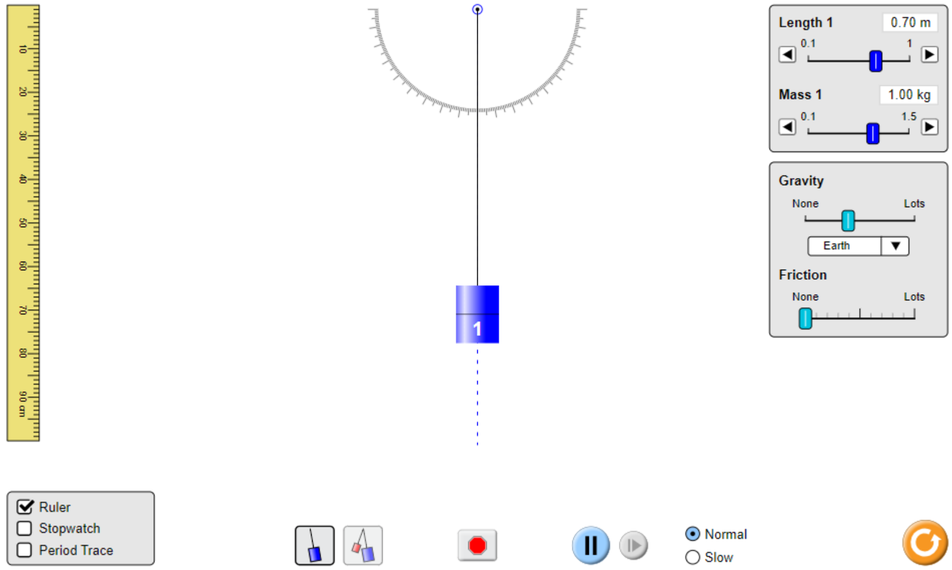


Figure 2.4: A PhET simulation illustrating the dependence of pendulum motion on the length of the pendulum, the mass of the pendulum bob, the magnitude of the local acceleration due to the gravity, and any frictional forces.

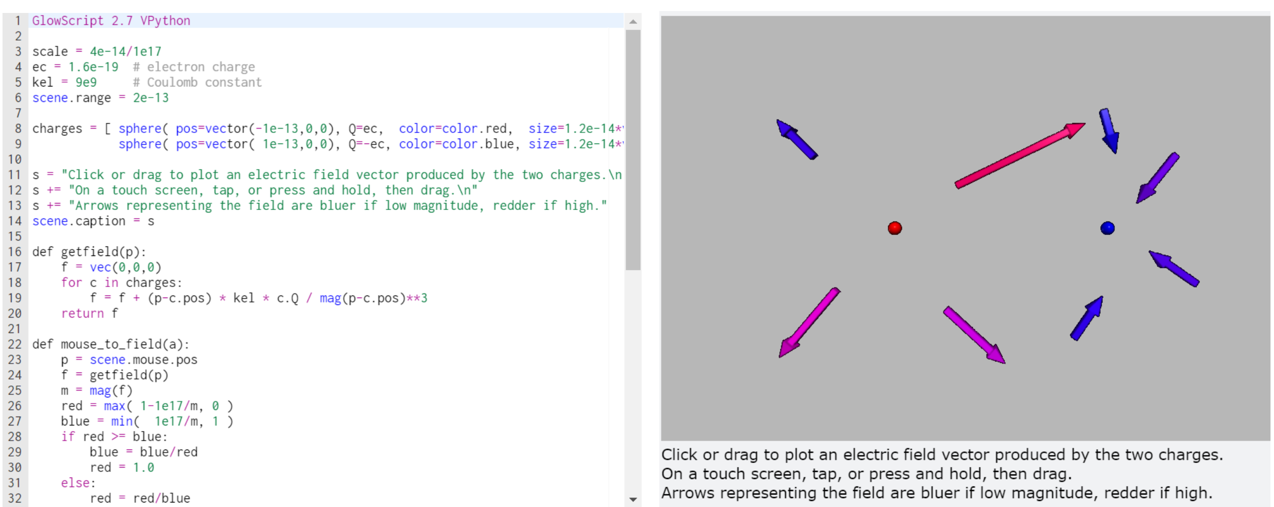


Figure 2.5: Glowscript output demonstrating its ability to generate three-dimensional visualizations of objects, vectors, and graphs. The ability to quickly and accurately generate three-dimensional vectors allows for more flexibility and a deeper understanding of electric fields.

Some of the critical results, though, are described below.

2.2.2 Prior findings

In the early 2000s, Chabay began to research the integration of computation into the introductory calculus-based physics course using VPython [9]. This course included a computational curriculum following that presented by *Matter and Interactions.* Primarily, the courses studied by Chabay focused on the application of the integral equation governing the linear motion of objects (i.e., $d\vec{p} = \vec{F}_{\text{net}}\,dt$ and $d\vec{r} = \vec{p}/m\,dt$). These equations were applied iteratively through an Euler-Cromer style integration algorithm, and allowed a more thorough analysis of position-dependent forces (e.g., the spring force).

Chabay found that one of the positive aspects of including computation at the introductory level was to stimulate creativity in students [9]. This creativity in approaching problem solving is thought to lead students to the construction of more realistic computational models. In other words, computation allows students to easily verify and/or modify a model, encouraging creativity and an "educated guess and check" approach to problem solving.

She also found that requiring students to program at the introductory physics level was a difficult barrier to overcome. Given that there is so much content to be covered in so little time in most introductory physics courses, finding the room/time to discuss the basics of programming is difficult. One of the ways in which this difficulty is overcome is by providing Minimally Working Programs (MWPs) to students. The MWP for a particular problem usually runs without error from the start, and requires small (or at least localized) changes to the underlying computational models. For example, see the MWP in Fig. 2.7 and its different components.

Around that same time, Kohlmyer dug deeper into student performance [10]. He found that, among other things, computational modeling students struggled to recognize that computers could even be used to solve physics problems. Furthermore, once they did decide to use a computer, they struggled with the concepts and components of creating a computational model. These results were generated from two experiments: looking at how students approach novel problems with computation and looking at the differences in the fundamental principles used as compared to traditional (i.e., a non-computational curriculum) students. Interestingly, he found that students decided to take advantage of the Euler-Cromer style integration in discrete form even when they weren't using a computational model. That is, students made use of the key conceptual tool that they were taught – even if just on paper.

He also found that the complex procedure needed to model attractive position-dependent forces was a difficult challenge for students. Reducing this and other difficulties can be achieved through increasing the frequency of computation throughout the course or requiring computational homework problems. However, Kohlmyer made explicit the wide variety of unanswered questions that could be pursued in further research, hinting that the process of "making assumptions" and incorporating them into a computational model would be of particular interest.

In 2011, Weatherford began to look at integrating computation into the physics lab curriculum and the sense-making that students engage in [29]. His study was an in-depth qualitative analysis of group problem solving, focusing on three different contexts: a scattering problem, a spring-mass problem, and a spacecraft-Earth problem. A coding scheme was developed to help categorize different portions of transcript, as shown in Fig. 2.6.

He found, among other things, that computational physics students were able to reasonably interpret physical quantities according to their variable name. For example, the mass of a satellite might be defined as `m.satellite = 1`, or the net force acting on an object may

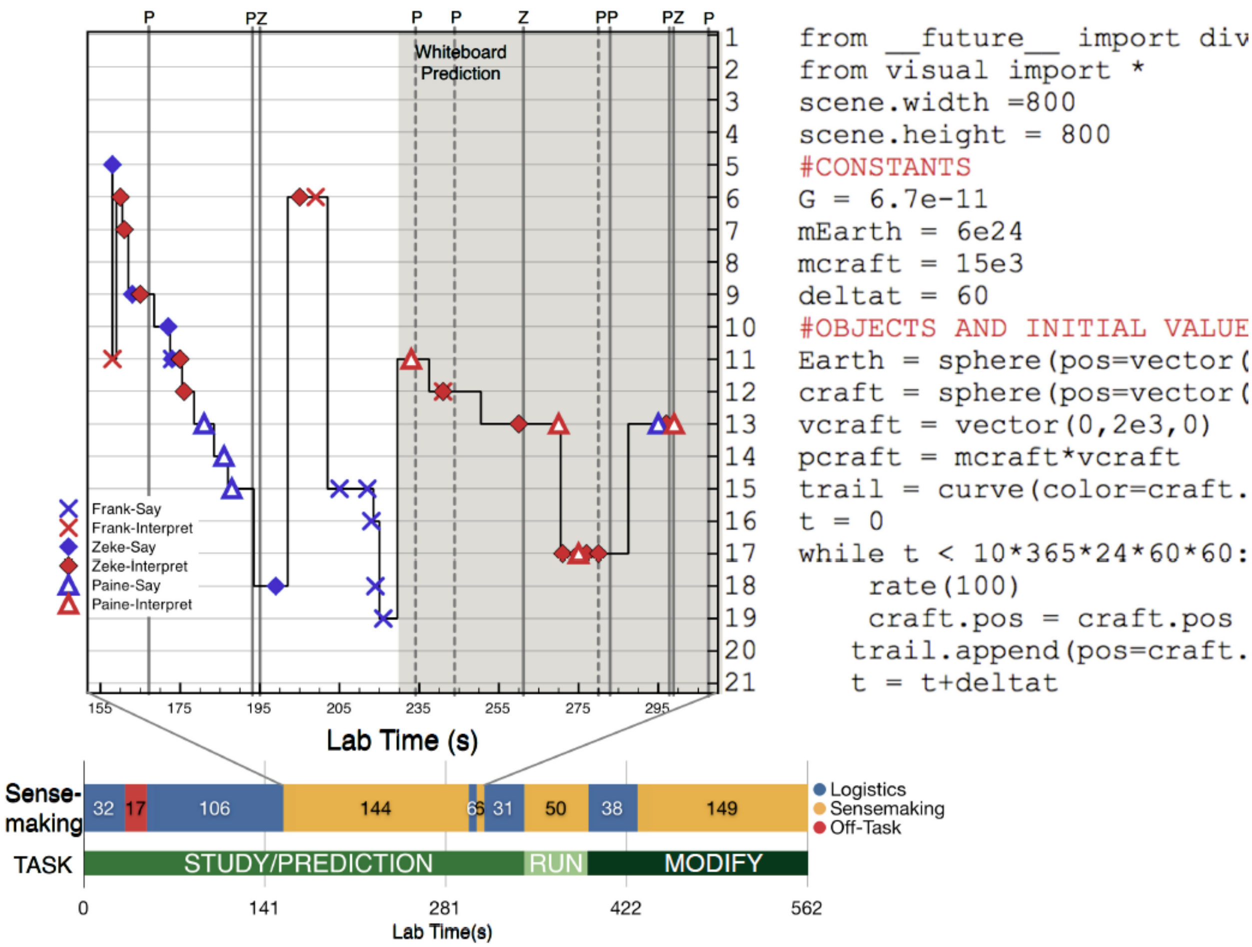


Figure 2.6: A sample of the in-depth analysis Weatherford performed. Each particular line of code that the group is focusing on is tracked in time and coded according to a researcher-developed scheme.

be defined as `Fnet = vector(0,-m*g,0)`. These pre-written variables are named so as to suggest to the students what physical quantity they represent. However, the more complicated the definitions get (e.g., a function of multiple variables like `Fnet = -k * (ball.pos - origin.pos) / mag(L)`, the more students struggled at recognizing it.

Additionally, Weatherford was able to encourage students to begin to incorporate a computational model in a MWP by providing a minimum level of support. That is, only omitting the fundamental physics calculations that students are meant to engage with (e.g., various computational force models) helps to keep students focused on the physics. Other tasks that are not physical in nature have a tendency to derail the physics discussion and the problem solving process in general. For example, ensuring that the end of a spring is connected to the end of a mass in a computational spring-mass analysis begins to overshadow the more fundamental task of incorporating/constructing a position-dependent linear spring force. Similarly, figuring out how to use the `mag()` function in Python can sidetrack the ultimate goal of constructing a position dependent gravitational force.

Weatherford clearly pointed out that the MWP activities in their study had much room for improvement, and that more research was needed on fostering student proficiency in computational physics. The sequence of MWPs in his study didn't quite raise students' program comprehension and program interpretation skills to a certain proficiency, but he believes that more research will shed light on the subject.

In 2011, Caballero was able to identify a number of frequent student mistakes with a satellite-Earth MWP, shown in Fig. 2.7, that were grouped into three different categories: initial condition mistakes, force calculation mistakes, and second law mistakes [31]. An initial condition mistake might take the form of an incorrect initial velocity or momentum of the satellite. A force calculation mistake might manifest in a constant spring force rather than

```
while t <tf:

    r = craft.pos-Earth.pos
    rhat - r/mag(r)                                    Force calculation
    Fgrav = -G*mEarth*mcraft/mag(r)**2*rhat

    pcraft = pcraft + Fgrav*dt                         Newton's second law
    craft.pos = craft.pos + pcraft/mcraft*dt           Position update

    trail.append(pos = craft.pos)
    t = t + dt

print 'Craft final position: ', craft.pos, 'meters.'
```

Figure 2.7: An expected solution to a computational satellite-Earth problem where the Newtonian gravitational force has been constructed from a separation vector and its magnitude. The force calculation has been incorporated into the momentum through Newton's second law, and the momentum is incorporated into the position through a position update.

a position dependent spring force. A second law mistake might involve missing the division of the mass from the net force on an object so that the velocity is correctly updated according to the acceleration. These frequent mistakes result in both unexpected and physically inaccurate visualizations.

Based on his analysis of the satellite-Earth problem, Caballero concluded that the majority of students ($\sim 60\,\%$) were able to correctly computationally model novel physics problems and that, among other things, the practice of debugging would serve students well. Particularly, the act of troubleshooting syntax errors as well as the act of troubleshooting physics errors.

2.2.3 Remaining questions

Although many aspects of computation and computational thinking at the introductory level have been studied, there are still many unanswered questions within physics education. Particularly, as to the types of practices students are engaging in that are indicative of computational thinking. More research is needed to not only more clearly define the computational practices observed in introductory physics, but also to more clearly understand the habits of mind and types of thinking that students are engaging in. This thesis attempts to provide clear and precise definitions of the various practices, indicative of computational thinking, that students engage in within introductory physics.

2.3 Framework

Recently, a framework for identifying the computational practices that are indicative of computational thinking has been proposed by Weintrop et. al [7]. This framework was developed using existing literature on computational thinking, interviews with mathematicians and scientists, and computational activities from general science and mathematics classrooms.

In order to develop their framework, a literature review was performed to generate an initial set of 10 math and science practices. These initial practices are repeatedly cited by Weintrop et. al as being central to computational thinking. For example, the broad and repeatedly cited practice of generating algorithmic solutions might require a student to engage with a differential equation algorithm. These broad initial practices were used to guide the subsequent qualitative analysis.

Using the initial practices resulting from the literature review, two reviewers independently coded for the various "facets" of computational thinking that were required by the curricular materials. They analyzed 32 different computational activities from chemistry to programming, resulting in 208 facets which were grouped into 45 different practices.

Next, a review process incorporating feedback from multiple sources (e.g., teachers, content experts, and curriculum designers) was used to reduce the 45 practices into 27, which were further organized into 5 different categories. Further, external interviews were conducted with 16 K-12 science and mathematics teachers, helping to reduce the 27 practices into 22 fitting 4 different categories, summarized in Tab. 2.1.

Data	Modeling	Solving	Systems
Creating	Concepts	Preparing	Investigating
Collecting	Testing	Programming	Understanding
Manipulating	Assessing	Choosing	Thinking
		Creating	Communicating
		Debugging	Defining

Table 2.1: The framework developed by Weintrop et. al to describe the computational practices observed in science and mathematics classrooms. Each category contains between five and seven individual practices, and each practice has between two and seven fundamental characteristics.

Finally, 15 interviews with STEM professionals were conducted to rate their framework according to its applicability to authentic professional practices and to give direction for future improvement. For example, interviews showed that the practice of testing and debugging was a crucial practice (see Sec. 2.7) that was not adequately captured by the framework – an improvement that should be made on future iterations of the framework.

The four different categories of practices are labeled as data, modeling and simulation, computational problem solving, and systems thinking practices. The data practices focus mostly on the creation and visualization of data. The modeling and simulation practices focus mostly on the design, construction, and assessment of a computational model. The problem solving practices focus mostly on programming and debugging, while the systems thinking practices are more abstract and focus mostly on the structure of the program itself.

As a more concrete example, the computational practice of creating data, one of the data practices, has three fundamental characteristics: the creation of a set of data, an articulation of the underlying algorithm, and a use of the data to advance understanding of a concept.

The more of the characteristics that we observe in a particular situation, the more confident we are that that situation can be classified as that practice.

Although each practice is defined like this, according to Weintrop et. al, the characteristics themselves are rather vague – similar to the operational definitions from the NGSS. For example, the computational practice of assessing computational models requires the identification of a phenomenon, a computational model, and a comparison made between the two. Although it is clear what a comparison would look like in any situation, the phenomena studied and the models used will depend greatly on the context (see Ch. 3). For this reason, more work must be done to clearly define computational thinking within introductory physics classrooms.

Ultimately, Weintrop found three main benefits to including computation: it builds on the reciprocal relationship between computational thinking and STEM domains, it engages learners as well as instructors, and it introduces an authentic and modern element of doing science. However, he is clear to indicate that more research is needed to better address the challenge of educating a technologically and scientifically savvy population. This thesis attempts to improve that education process by providing clear and precise definitions with examples of the computational practices that are indicative of computational thinking at the introductory physics level. Accordingly, we have used both a task and thematic analysis, described in the sections that follow, to facilitate those clear and precise definitions.

2.4 Task analysis

A task analysis is a procedure that can be used to better understand the requirements of a particular task and the way an "operator" (or group of operators) might work to satisfy those requirements [32]. This type of task analysis is usually focused on the observable actions that an operator might engage in while working toward a particular goal (e.g., producing a graph or diagram), but there is also a strong cognitive link between the observed actions and the requirements of the task [33]. This indispensable type of procedure helped us to focus on the most important steps that students were taking while solving problems.

Before beginning a task analysis, data must first be collected. Often, the method for data collection is observation based (e.g., observing the actions of a group of operators as they carry out a task), although data can also be subject based (e.g., asking an expert what the ideal actions would be to carry out a task). Either way, the task itself generally guides the collection of data.

Once the data has been collected, there are different types of descriptions that can be attached to it and different techniques that can be used to generate them. For example, one of the techniques frequently used is to *chart and network* the data. These descriptions can be written, but are most often presented visually through information flow charts or Murphy diagrams. This thesis leverages a technique for generating an *organized hierarchy* of description of the data: complex tasks are broken down into multiple smaller but more manageable tasks.

This type of task analysis is frequently used in the fields of mathematics and computer science [34, 35, 36, 37]. The smaller but more manageable sub-tasks are the "unit of analysis" that can then be searched for within data. For example, an expert group might proceed in predicting the motion of an object by first constructing an Euler-Cromer style algorithm, constructing the various forces, and then constructing the initial parameters of the system. These steps can be done in any order, but are all necessary to the overarching task.

This type of process was used by Catrambone to show that breaking a problem down into smaller but more manageable sub-tasks helps students to transfer knowledge to new and novel problems [34]. He believes that it is a hierarchical structure of tasks rather than a linear structure of tasks that students need to transfer knowledge to new and novel situations. The flexibility of a hierarchical structure is thought to support a more expert approach to solving problems.

Step (Sub-Task)	Associated Code
Construct separation vector between interacting objects	sep = obj2.pos - obj1.pos
Construct the unit vector	usep = sep/mag(sep)
Construct the net force vector	Fnet = -G*m1*m2*usep /mag(sep)**2
Integrate the net force over time into momentum	obj.p = obj.p + Fnet*dt

Table 2.2: Some of the necessary steps that must be taken when constructing a Newtonian gravitational force in code. Each step is associated with the construction/modification of a line of code.

Catrambone performed three experiments, each focusing on how students transfer knowledge to new and novel problems. The first experiment was a comparison between the meaningfulness of a label's name. He found that the more meaningful the label was, the better prepared students were to solve new and novel problems. The second was a deeper study of the connections between labels and sub-tasks. He found, to a reasonable degree, that there was a fundamental connection between labels, sub-tasks, and how they were grouped. The third was a talk-aloud study that looked at self-explanation while solving problems. He found that aptly named labels could be used to cue students to group sub-tasks and explain their purpose through self-explanation.

Although we have used the concept of a task analysis to help focus on specific aspects of our data, we have not used it in the same way as Catrambone. There are a myriad of expected and unexpected tasks that students engage in while solving a particular problem in any type of classroom. For example, taking the time to name a variable with meaning, working to construct a multiple-variable function, or changing the color of an object within a program. Given the almost limitless number of tasks that might draw students' (and our) attention, the task analysis was used to reduce the initial set of tasks that we focused our attention on. This initial set of tasks was modified and expanded during subsequent qualitative analysis (see Sec. 2.5).

The task analysis of the problem that this thesis focuses on was initially constructed by a single content expert. After the first iteration it was presented to additional experts. Through the discussions surrounding these iterations, it became clear that the construction of the position dependent Newtonian gravitational force in code is a multi-step procedure involving a number of different sub-tasks. The task analysis was iteratively refined through this process until all experts agreed that the sub-tasks shown in Tab. 2.2 were sufficiently described/defined to be useful in video analysis.

On top of this expert generated solution, there are many other (both expected and unexpected) student generated solutions that we observe in the data. However, the expert generated solution is an ideal path to follow and so the instructors try to keep groups moving in this direction. For example, a sufficient force model can be constructed in terms of the polar and azimuthal angle of the satellite, although it requires a substantial amount of work to code. Both the expert and student generated solutions are a good place to look for evidence of computational thinking and its accompanying practices.

2.5 Thematic analysis

Thematic analysis is a commonly used type of qualitative analysis that is commonly used within psychology. However, Braun makes the well-supported case that thematic analysis can effectively be used in many other fields (e.g., nursing or physics education) and clearly defines the sufficient steps that can be taken in order to complete a reasonably reliable and valid thematic analysis [38, 39, 40, 41, 42, 43, 44].

Within PER, thematic analysis is usually used for analyzing interview or work-aloud data of students solving problems. For example, Irving found that there were many different themes that came from the various perceptions students have about what it means to "be a physicist" [45]. These themes were then broken down into 12 sub-categories (e.g., high or low interest in research), highlighting the different perceptions students had about what it means to "do physics." This type of analysis, as demonstrated by Irving, can be used to generate robust themes that can be used to inform instructional changes/improve instruction.

However, thematic analysis is just one of many qualitative techniques that can be used to analyze qualitative data. The various qualitative methodologies can be broken into roughly two main types: those strongly tied to a theory/epistemology and those that are developed independent of a guiding theory/epistemology. Thematic analysis, according to Braun, is of the second type. So as to guard against the often cited critique of thematic analysis as being ill-defined [44], Braun presents a method to conducting a reliable and valid thematic analysis.

This method consists of 6 different phases, usually followed linearly, to finally produce a report (e.g., a thematic map) of the various themes and their relationships within a set of qualitative data. However, before entering the first of the 6 phases, there are a few fundamental decisions that must be made and explicitly stated. Ideally, these decisions will be made in relation to the research question and the goal of the study.

First, it is crucial that researchers explicitly state the metric by which they plan to identify themes. For example, a theme that shows up more frequently is not necessarily more important. Additionally, a theme that shows up less frequently is not necessarily less important. Rather, it is important to be consistent throughout analysis. This thesis mostly focuses on the more frequent themes, but consideration is also given to themes that are particularly illustrative yet infrequent.

Second, researchers must decide between a rich description of the entire data set or a more detailed account of a particular sub-set. For example, within physics education, you might be interested in a rough description of the entire process that a group followed to successfully solve a complicated problem. Alternatively, you might want to focus in on a particular sub-task and its nuance. This thesis focuses on a more detailed account of a particular sub-set of the themes (i.e., those involving computational thinking).

Third, researchers must decide between an inductive and a more theoretical approach to the generation of themes within their data. An inductive approach often leads to themes that are not related to the original research questions, but rather are emergent during analysis and are more strongly tied to the data itself. A theoretical approach, on the other hand, often leads to a set of themes that are less descriptive but are better suited to answer a particular research question. This thesis follows a more theoretical approach, using the theoretical framework presented in Sec. 2.1 as a foundation for the generation of our themes.

Fourth, researchers must decide whether they will be looking for semantic or latent themes within their data. Semantic themes are those that are clearly indicated within the data, whereas latent themes often go beyond what is actually being observed. For example, within physics education, a group of students might be struggling with a particular problem. The reason for this struggle might otherwise go unnoticed without looking beyond the immediate and recognizing that each student had a late and mentally taxing chemistry exam the previous night. Usually a thematic analysis focuses on one level – this thesis primarily focuses on the semantic themes that are directly tied to the actions observed during the problem solving process.

Fifth, researchers must choose between an essentialist and a social constructionist thematic analysis. An essentialist thematic analysis allows researchers to theorize student understanding and meaning in a straightforward way [43, 46]. A social constructionist approach focuses more on the overarching sociocultural and structural environment that each student lives within. This thesis focuses on a more essentialist approach, paying special attention to the computational thinking and habits of mind that students are engaging in.

Once these decisions have been made, the qualitative analysis can proceed through the 6 phases laid out by Braun. The first phase focuses on (1) transcribing and familiarizing yourself with the data. Reading through the transcripts multiple times helps to generate preliminary ideas that can be (2) coded for further investigation. Next, each code must be (3) collated with the corresponding transcript so as to provide a context. After the codes have been collated with the corresponding transcript, (4) themes begin to emerge. Reviewing any themes that emerge, particularly against the coded extracts and the transcript as a whole, leads to the next phase of (5) defining, validating, and naming any themes. These themes can finally be presented in a (6) scholarly report with step-by-step transcript analysis and/or a thematic map. A thematic map, like the one shown in Fig. 2.8, shows not only the components of a theme, but also the *relationships* between those components.

Braun is clear to point out that there are many pitfalls associate with thematic analysis,

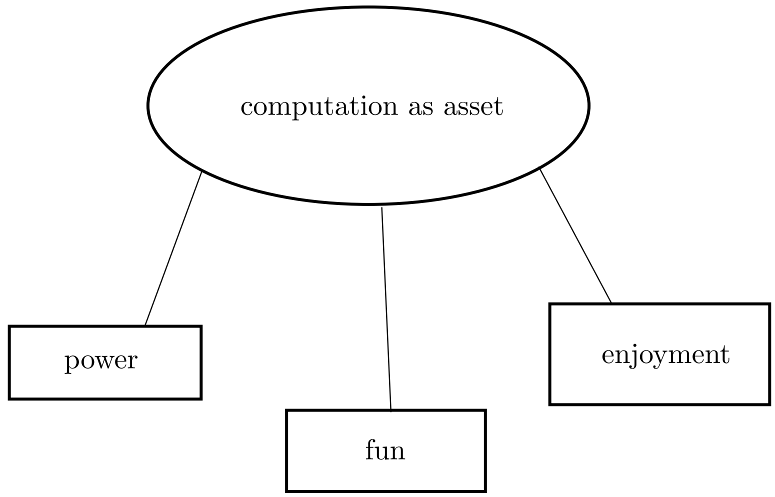


Figure 2.8: A final thematic map showing the components of a theme named "computation as asset." The main components of this theme are "power," "fun", and "enjoyment."

and that researchers must be cognizant of them through every phase of the process. For example, one of the pitfalls she highlights is a possible mismatch between the data and the analytic claims that are being made. In other words, it is important to always closely tie your claims to the actual data. This closeness of the claims to the data can be ensured through frequent inter-rater reliability checks.

As we have shown, thematic analysis is a powerful and flexible qualitative methodology. Accordingly, this thesis leverages thematic analysis to guide our study of group problem solving in introductory computational physics with the hopes of highlighting the various practices students engage in that are indicative of computational thinking. A detailed account of this process is described in Sec. 5.

Chapter 3

Context

It is important to understand the course from which we have collected our data to better understand the results of our study. That course – called Projects and Practices in Physics (P^3) – is based on a social constructivist theory of learning and a flipped/problem-based pedagogy [47]. In other words, students familiarize themselves with relevant material before coming to class, where they will work in small groups to actively and socially construct knowledge while solving complex analytical and computational physics and engineering problems. The course has intentionally been designed to encourage computational thinking wherever possible. Specifically, computational thinking has been incorporated into the notes, pre- and post-class homework, in-class feedback and assessments, and a selection of the in-class problems.

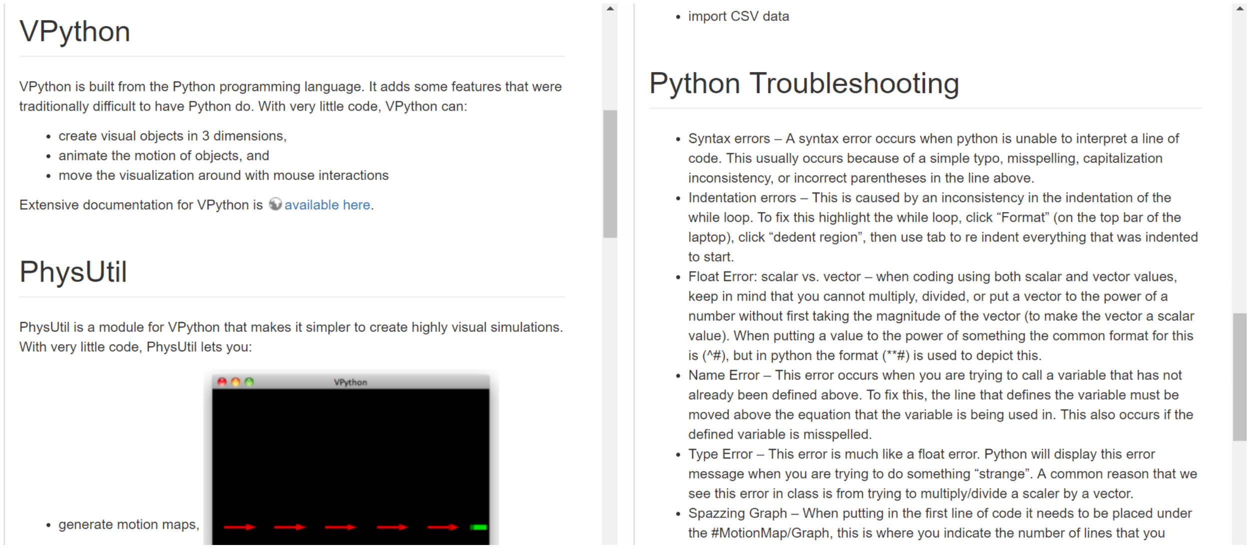
3.1 Course schedule

Each week in P^3, students are expected to accomplish a number of tasks. They must complete the pre-class homework which is based on information that they should gather from the pre-class notes. They must then work in small groups (usually between three and four members) on two related analytical problems or a mixture of one analytical and one related computational. These problems are delivered during the two two-hour weekly meetings (See Fig. 3.1). For the computational problem, that means reading and interpreting pre-written code (i.e., a minimally working program) while they design, assess, and construct various computational models. The small group is facilitated by either a course instructor, graduate teaching assistant, or undergraduate learning assistant who will ask relevant and pertinent follow-up questions to check for conceptual understanding. There are also post-class homework questions based on information gathered from the pre-class notes and the in-class problems that are due at the end of the week. This all occurs while students simultaneously prepare for the following week.

3.2 VPython

Given that the vast majority of students enter P^3 with little to no prior programming experience, we need to ensure that they are prepared to handle computational problems early in the semester. One way that we can ensure this is by requiring students to engage with the fundamental programming ideas (e.g., iteration through a while loop control structure or pre-defined mathematical functions) before coming to class through pre-class homework and notes. These notes and homework questions highlight the fundamental physical and programming ideas specific to VPython and the computational problems that will be delivered in class.

For example, consider the portion of the course notes shown in Fig. 3.1. These notes are made available to the students at the beginning of the semester and are meant to provide students with a basic understanding of the utility of VPython along with a list of common errors that novice programmers must frequently deal with. These notes provide not only a description of the error, but also a procedure for removing it while students are troubleshooting code. Troubleshooting and debugging are two of the problem solving practices indicative of computational thinking that we focused our analysis on.



VPython

VPython is built from the Python programming language. It adds some features that were traditionally difficult to have Python do. With very little code, VPython can:

- create visual objects in 3 dimensions,
- animate the motion of objects, and
- move the visualization around with mouse interactions

Extensive documentation for VPython is available here.

PhysUtil

PhysUtil is a module for VPython that makes it simpler to create highly visual simulations. With very little code, PhysUtil lets you:

- generate motion maps,

- import CSV data

Python Troubleshooting

- Syntax errors – A syntax error occurs when python is unable to interpret a line of code. This usually occurs because of a simple typo, misspelling, capitalization inconsistency, or incorrect parentheses in the line above.
- Indentation errors – This is caused by an inconsistency in the indentation of the while loop. To fix this highlight the while loop, click “Format” (on the top bar of the laptop), click “dedent region”, then use tab to re indent everything that was indented to start.
- Float Error: scalar vs. vector – when coding using both scalar and vector values, keep in mind that you cannot multiply, divided, or put a vector to the power of a number without first taking the magnitude of the vector (to make the vector a scalar value). When putting a value to the power of something the common format for this is (^#), but in python the format (**#) is used to depict this.
- Name Error – This error occurs when you are trying to call a variable that has not already been defined above. To fix this, the line that defines the variable must be moved above the equation that the variable is being used in. This also occurs if the defined variable is misspelled.
- Type Error – This error is much like a float error. Python will display this error message when you are trying to do something “strange”. A common reason that we see this error in class is from trying to multiply/divide a scaler by a vector.
- Spazzing Graph – When putting in the first line of code it needs to be placed under the #MotionMap/Graph, this is where you indicate the number of lines that you

Figure 3.1: Portion of on-line notes that is made available to the students during the first week of the course. These notes introduce the fundamental programming ideas and a list of common errors with tips and tricks.

3.3 Pre-class work

There are other weekly notes, made available to the students at the beginning of every week, focusing more on the fundamental physical ideas that will be used during class. For example, during the third week the notes focus on uniform circular motion (most heavily used during the week’s analytical problem) and the Newtonian gravitational force (most heavily used during the week’s computational problem).

Aside from notes, material is also delivered to the students through weekly pre-class homework questions. Consider the pre-class homework question shown in Fig. 3.2 that is made available at the beginning of the third week of the course. This question is meant to demonstrate that there are multiple correct ways that a unit vector can be constructed in code. Given the nature of the corresponding week’s computational problem, we expect students to be able to draw on and take advantage of this knowledge when faced with a related albeit more complicated problem in class. That is, we expect students to be choosing between competing solutions. Choosing between competing solutions is a problem solving practice indicative of computational thinking that we focused our analysis on.

9. Calculating a unit vector in VPython

Students in your class are continuing to model the motion of Triton (one of Neptune's 13 moons) around Neptune, but now using VPython. The code your class has received contains the following snippet of VPython code.

```
Neptune = sphere(pos=vector(100,200,300), radius=1)
Trion = sphere(pos=vector(10,20,30), radius=2)
```

(a) From this snippet, which of the following lines of code might your group write to describe the separation vector pointing from Neptun to Triton?

```
○ rvec = Triton.pos - Neptune.pos
○ rvec = Neptune.pos - Triton.pos
```

(b) Several groups have written different lines of code to calculate the magnitude of the separation vector; some are correct and some are not. From your understanding of the line(s) of code below, which of them correctly represent the magnitude of the separation vector?

```
☐ rmag = mag(Neptune.pos) - mag(Triton.pos)
☐ rmag = mag(Triton.pos - Neptune.pos)
☐ rmag = sqrt((Triton.pos.x - Neptune.pos.x)**2
              +(Triton.pos.y - Neptune.pos.y)**2
              +(Triton.pos.z - Neptune.pos.z)**2)
☐ rmag = sqrt((Neptune.pos.x - Triton.pos.x)**2
              +(Neptune.pos.y - Triton.pos.y)**2
              +(Neptune.pos.z - Triton.pos.z)**2)
☐ rmag = mag(Neptune.pos - Triton.pos)
☐ rmag = mag(Triton.pos) - mag(Neptune.pos)
```

Figure 3.2: Pre-class homework question focusing on the different ways that the magnitude of a vector can be constructed in VPython code: explicitly coding the square root of the sum of the squares of the components and using the pre-defined Python "magnitude" function.

3.4 In-class work

There are a number of in-class computational problems spread out throughout the semester, scheduled in Tab. 3.1. The first few computational problems focus on different force models (i.e., no force, a constant force, a non-constant force) and the resulting motion of objects. The last few computational problems focus on extended objects and their rotation. While

	Monday	**T**uesday	**T**hursday	**S**unday
W1	Pre-H1 due	A1: constant velocity motion	C1: constant velocity motion	Post-H1 due
W2	Pre-H2 due	A2: constant acceleration motion	C2: projectile motion	Post-H2 due
W3	Pre-H3 due	A3: Satellite orbit	C3: Newtonian gravitational force	Post-H3 due
W4	Pre-H4 due	A4a: Spring force	A4b: Young's modulus	Post-H4 due
W5	Pre-H5 due	A5a: Friction	A5b: Friction	Post-H5 due
W6	Pre-H6 due	A6a: Circular motion	A6b: Circular motion	Post-H6 due
W7	Pre-H7 due	A7a: Gravitational potential energy	A7b: Spring potential energy	Post-H7 due
W8	Pre-H8 due	A8: Energy	C4: Energy	Post-H8 due
W9	Pre-H9 due	A9a: Heat	A9b: Thermal energy	Post-H9 due
W10	Pre-H10 due	A10a: Rolling motion	A10b: Rotational energy	Post-H10 due
W11	Pre-H11 due	A11: Elastic collisions	C5: Inelastic collisions	Post-H11 due
W12	Pre-H12 due	A12a: Statics	A12b: gears	Post-H12 due
W13	Pre-H13 due	A13: Angular momentum	C6: Angular momentum	Post-H13 due
W14	Pre-H14 due	A14: Angular collisions	C7: Angular collisions	Post-H14 due
W15	Pre-H15 due	A15a: Choose your own adventure	A15a: Choose your own adventure	Post-H15 due

Table 3.1: A schedule for the semester focusing on topics covered, homework/reading deadlines, and in-class problems.

solving these problems, groups are expected to engage in a number of practices that the problems have been designed around [5]:

P1. developing and using models,

P2. planning and carrying out investigations,

P3. analyzing and interpreting data,

P4. using mathematics and computational thinking,

P5. constructing explanations,

P6. engaging in argument from evidence.

P7. and obtaining, evaluating, and communicating information.

One of the scientific practices used heavily on both analytic and computation days is that of (P1) developing and using models. Whether those models be mathematical or computational, we expect students to not only work together in groups to develop the model, but also to utilize that model in further investigations. This type of scientific practice (P1) and its associated learning goals [47] were further used to generate the in-class project that this thesis focuses on.

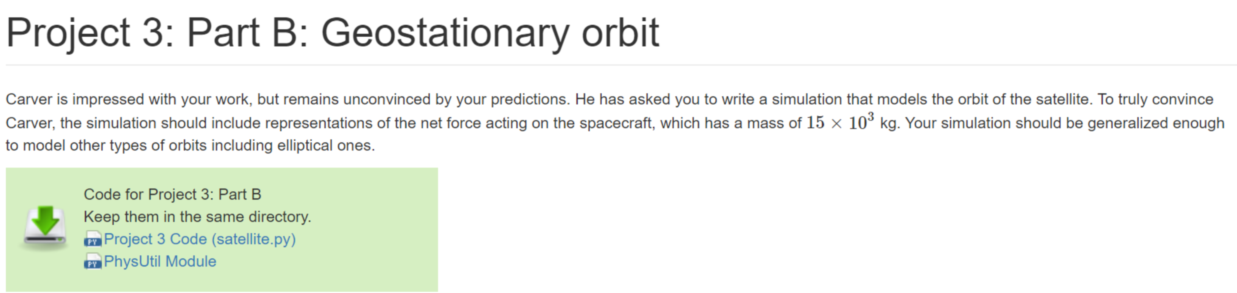
3.4.1 Analytic problem

In the third week of the course, students are asked to analyze the motion of a satellite orbiting Earth both analytically and computationally. For the analytic day, the groups were asked to solve for the magnitude of the velocity and radius needed by a satellite to be held in a geostationary orbit. This involves identifying two relevant equations in two unknowns and combining them to solve for the desired radius and magnitude of velocity. The information gathered during this problem can be used in the following computational problem, and the group facilitators are often observed referencing this information.

3.4.2 Computational problem

This thesis focuses on the third and most complicated computational problem delivered to the students, shown in both Figs. 3.1 and 3.3. Given its complexity, we developed a framework to help guide and ground our analysis. This framework was constructed with the help of a task analysis (see Sec. 2.4) of the problem. Ultimately, students must design, construct, and asses a computational model for the Newtonian gravitational force acting on a satellite in geostationary and other more general orbits.

Once the correct force has been correctly coded, the group must also grapple with adding in a visualization of a vector representing the force that they have just added. This type of motion diagram is meant to show that the gravitational force vector resulting in the orbit always points radially inward (toward the Earth). This task requires students to



Project 3: Part B: Geostationary orbit

Carver is impressed with your work, but remains unconvinced by your predictions. He has asked you to write a simulation that models the orbit of the satellite. To truly convince Carver, the simulation should include representations of the net force acting on the spacecraft, which has a mass of 15×10^3 kg. Your simulation should be generalized enough to model other types of orbits including elliptical ones.

Code for Project 3: Part B
Keep them in the same directory.
Project 3 Code (satellite.py)
PhysUtil Module

Figure 3.3: The Newtonian gravitational force problem statement delivered to the students in the third week of class.

program as well as allows them to more easily check their conceptual understanding. Using computational models to understand a concept is a computational modeling and simulation practice that is indicative of computation thinking, and one that we focused our analysis on.

Additionally, in order to check that their model can produce a geostationary orbit, groups are asked to generate a graph showing the magnitude of the separation between the satellite and the center of the Earth vs. time. This allows them to check for a constant distance which implies a circular orbit. This task of producing a graph is meant, among other things, to encourage students to visualize data, yet another computational practice indicative of computational thinking.

3.4.2.1 Minimally working programs

While beginning the problem, the group uses a Minimally Working Program (MWP) similar to those seen in the two previous computational problems listed in Tab. 3.1. This MWP has all of the structure of the code correct (the while/calculation loop and the Euler-Cromer integration) but is missing the computational force acting on the satellite (along with some inaccurate numerical values). The initial MWP code with its initial visualization are shown in Fig. 3.4.

Thus, the main task of the group is to construct a physically correct force model in code.

```
#Window setup
scene.range=7E7

#Objects
Earth = sphere(pos=vector(0,0,0), radius=6.4e6)
Satellite = sphere(pos=vector(7*Earth.radius, 0,0), radius=1e6)

#Parameters and Initial Conditions
mSatellite = 1
pSatellite = vector(0,5000,0)

#Time and time step
t = 0
tf = 60*60*24
dt = 1

#Calculation Loop
while t < tf:
    rate(10000)

    Fnet = vector(0,0,0)

    pSatellite = pSatellite + Fnet*dt
    Satellite.pos = Satellite.pos + (pSatellite/mSatellite)*dt

    t = t + dt

    #Earth Rotation (IGNORE)
    theta = 7.29e-5*dt
    Earth.rotate(angle=theta, axis=vector(0,0,1), origin=Earth.pos)
```

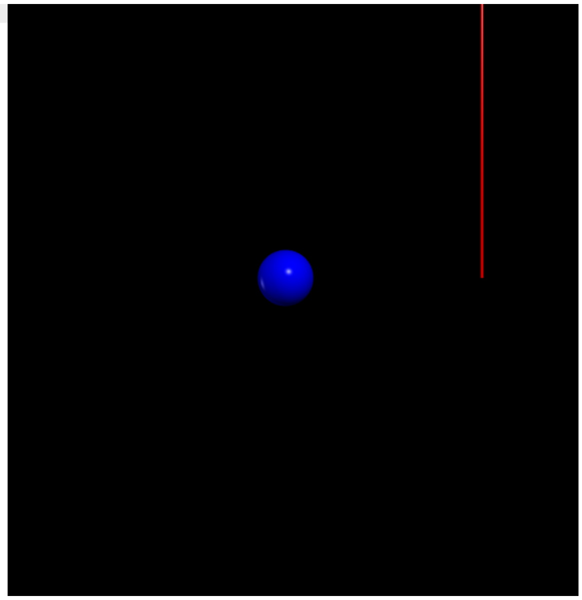


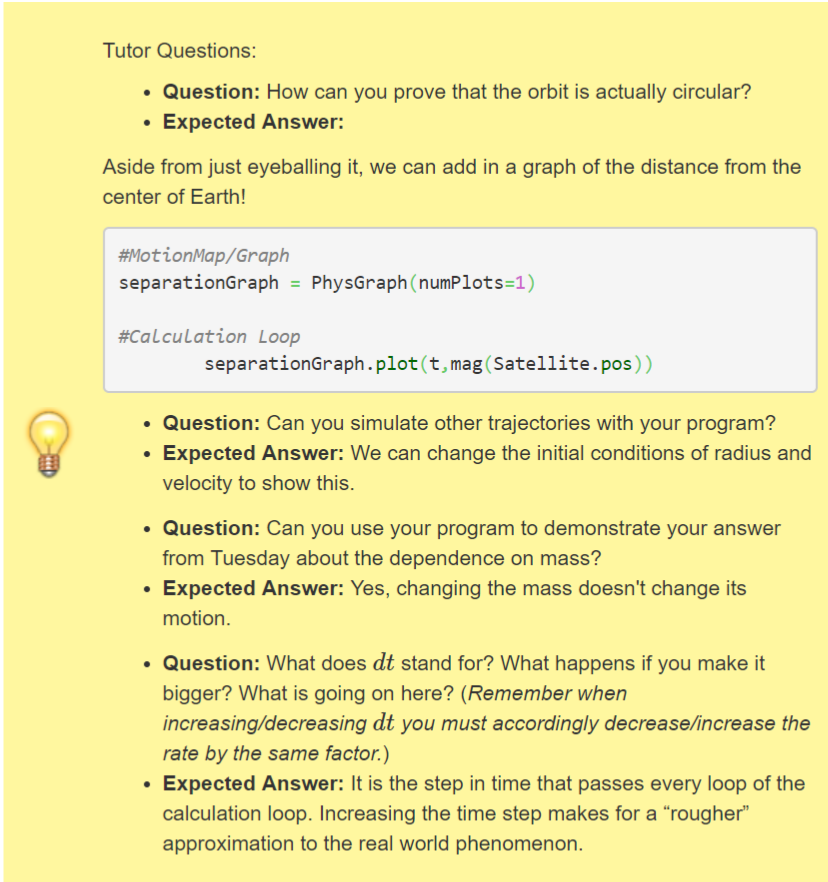
Figure 3.4: The initial code and visualization of the MWP that is given to the students in the third week of the course.

Secondarily, they must modify numerical values to reflect the phenomenon being modeled. Ideally, this force model will be of a Newtonian gravitational form (i.e., $F_G \sim 1/r^2$) with a direction coded in terms of a separation vector (i.e., $\hat{F}_G \sim \hat{r} \sim \vec{r}/r$). However, there are many other ways to go about this, and we do frequently observe groups working with other models (e.g., a centripetal force).

3.4.2.2 Tutor questions

There are a number of pre-written tutor questions as well as many on-the-fly questions generated by the tutors while in class. These questions are meant to check the students for conceptual understanding as well as to direct students toward the correct solution. For example, the tutor questions shown in Fig. 3.5 are meant to ensure that the model the group has constructed is actually general enough to generate all types of elliptical orbits given various initial conditions.

On the other hand, a tutor interaction like the one shown below that happens on-the-fly



Tutor Questions:

- **Question:** How can you prove that the orbit is actually circular?
- **Expected Answer:**

Aside from just eyeballing it, we can add in a graph of the distance from the center of Earth!

```
#MotionMap/Graph
separationGraph = PhysGraph(numPlots=1)

#Calculation Loop
        separationGraph.plot(t,mag(Satellite.pos))
```

- **Question:** Can you simulate other trajectories with your program?
- **Expected Answer:** We can change the initial conditions of radius and velocity to show this.

- **Question:** Can you use your program to demonstrate your answer from Tuesday about the dependence on mass?
- **Expected Answer:** Yes, changing the mass doesn't change its motion.

- **Question:** What does dt stand for? What happens if you make it bigger? What is going on here? (*Remember when increasing/decreasing* dt *you must accordingly decrease/increase the rate by the same factor.*)
- **Expected Answer:** It is the step in time that passes every loop of the calculation loop. Increasing the time step makes for a “rougher” approximation to the real world phenomenon.

Figure 3.5: A selection of tutor questions that focus on the computational model each group has constructed.

might encourage students to use a more general force rather than a more restricted one:

TA: You guys wanna talk about what your strategy is at the moment?

SB: I don’t think we know.

SA: We just, we need to figure out how to get the velocity of the spacecraft correct, as well as the force net correct, and then it should be fine...

TA: Yeah, my request, can I point in your program that’s what you have for F net now constant components.

TA: My request is to use a completely different strategy where that formula [points to

GmM/r^2 on the board] is in for Fnet.

SC: Yeah, we tried to make that, yeah...

SA: Can we just put the number in?

TA: Umm, in principle you could, but I'd really rather you not... I would like the program to be able to respond if the satellite is father away, so the force would be less, if the satellite is closer the force would be more...

TA: So I would like it to be a dynamic program and not one that always have a fixed force.

In this on-the-fly interaction, the question of weather or not their computational model will be able to handle all types of orbits is enough to indicate that the group needs to switch their model up. In this way, the tutor is able to make sure the groups stay on the desired path without directly telling them exactly what to do.

3.4.3 Feedback/Assessment

Groups are assessed on many levels in P^3. One of the most important forms of assessment is given weekly, in the form of written feedback and a numerical score. The written feedback is based on the observed in-class performance and is designed to point out deficiencies and suggests ways to improve. The numerical scoring is based on performance in three categories: group understanding, group focus, and individual understanding.

Often the written feedback pertains to group activity with the computer. For example, the portion of written feedback shown in Fig. 3.6 is encouraging a student to allow other group members to do some of the typing. This could be requested for any number of reasons

– most likely, though, because the students with less prior programming experience are not being given a chance to participate.

Feedback	Group Understanding	Group Focus	Individual Understanding
Doug, first and foremost let me say good job on working through a very difficult problem on Thursday. If you remember last feedback, we had hoped to see you plyaing more of an overseer role with VPython. Although we definitely saw more group involvement, not many other hands were doing the typing. It is going to be important that others have a chance at typing! For the future, try to use your familiarity with the computer to play more of a guiding role. As a post script, this will be your last feedback before our first exam. A few tips for success: it might be a good idea to have a designated scribe to make sure things are being written down in an organized and coherent manner. Also, don't forget to play what you are doing... Good luck!	3.25	3.5	3.25

Figure 3.6: A snippet of written feedback given to a student after the third week.

In this way, instructors can encourage their groups to share the programming load. While doing the typing, it is very difficult to follow along without knowing exactly what is going on. This helps to engage all of the students with the material.

3.5 Post-class work

There are a number of post-class homework questions that are meant to reinforce the physics and computational concepts seen in class. During the third week of the course, these questions focus mostly on the Newtonian gravitational force. However, the post-class homework question shown in Fig. 3.7 that is delivered in the third week focuses on the previous week's computational problem (i.e., it involves a local gravitational force as opposed to a Newtonian gravitational force). Nevertheless, this post-class question involves the same Euler-Cromer style of numerical integration as seen in all computational problems. The students are expected to use the error message in order to identify an error in the code.

```
  Traceback (most recent call last):
  File "ModelCar.py", line 16, in <module>
    car.pos = car.pos + vcar*dt
TypeError: unsupported operand type(s) for +: 'vector' and
'float'
```

The program as written appears below.

```
from visual import *

car = box(pos=vector(-120,0,0), size=(4.7,1.9,1),
color=color.red)
ground = box(pos=vector(0,-1,0), size=(300,1,1),
color=color.green)

mcar = 1050
vcar = 8.65

t = 0
dt = 0.01

while t < 0.6:

    rate(150)

    car.pos = car.pos + vcar*dt
    t = t + dt
```

Identify the error(s) in your program, indicate which line(s) should be changed, and write the line(s) that should be changed below:

Figure 3.7: A portion of a post-class homework question delivered in the third week of the course. This question requires students to troubleshoot and debug the code.

This type of problem helps to encourage students to identify, isolate, reproduce, and correct unexpected problems that arise while constructing computational models. Ideally, it requires students to interpret the names given to the variables being used and verify that they are defined in a correct form.

Chapter 4

Motivation

Aside from a general interest in introductory computational physics, it is important to understand the underlying motivation(s) for this thesis. Sections from the following chapter, detailing some of those motivations, were published in the proceedings of the 2015 Physics Education Research Conference [4], and are presented here with minor modifications from their appearance in publication. It was published with second and third authors Paul W. Irving and Marcos D. Caballero, respectively.

The process of identifying an interesting computational practice, described in Sec. 4.1, was the earliest motivation for this study. We found that it was extremely difficult to define and identify the particular practice of what we named "physics debugging." Not only did the practice need to be clearly defined, it also needed to be clearly identified in the data. This required a lot of in-depth qualitative analysis and inter-rater reliability, motivating our use of the Weintrop framework and the qualitative methods of Clarke et. al.

Additionally, we found that it was very difficult to understand the qualitatively different ways in which students experienced computational introductory physics. This difficulty motivated a task analysis with a focus on identifying practices that the students were engaging in through in-class observation, as opposed to their experiences through out-of-class interviews.

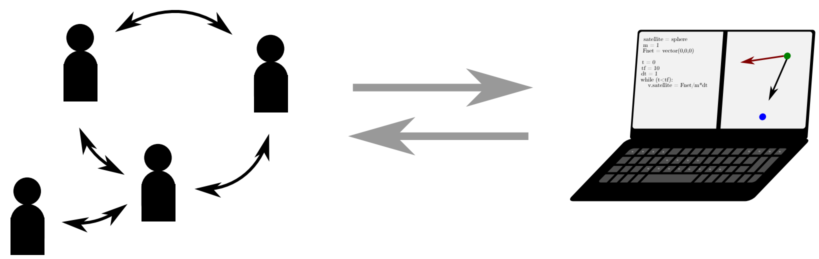


Figure 4.1: Interactions between individuals form a group, and the group interacts with the computer.

4.1 Debugging

In this section, we present a case study of a group of students immersed in this P^3 environment solving a computational problem. This problem requires the translation of a number of fundamental physics principles into computer code. Our analysis consists of qualitative observations in an attempt to describe, rather than generalize, the computational interactions, debugging strategies, and learning opportunities unique to this novel environment.

We focus this case study on the interactions between group and computer, illustrated in Fig. 4.1, to begin to understand the ways in which computation can influence learning. Particularly, we are interested in the interactions occurring simultaneously with social exchanges of fundamental physics principles specific to the present task (e.g., discussing $d\mathbf{r} = \mathbf{v}\,dt$ on a motion task) and the display of desirable problem solving strategies (e.g., divide-and-conquer). These group-computer interactions vary in form, from the more active process of sifting through lines of code, to the more passive process of observing a three-dimensional visual display.

One previously defined computational interaction that reinforces desirable strategies, borrowing from computer science education research, is the process of debugging [36]. Computer science defines debugging as a process that comes after testing *syntactically* correct code where programmers "find out exactly where the error is and how to fix it. [48]" Given the generic nature of the application of computation in computer science environments (e.g., data sorting, poker statistics, or "Hello, World!" tasks), we expect to see unique strategies specific to a computational *physics* environment. Thus, we extend this notion of computer science debugging into a physics context to help uncover the strategies employed while groups of students debug *fundamentally* correct code that produces unexpected physical results.

4.1.1 Analysis

In Fall 2014, P^3 was run at Michigan State University in the Physics Department. It was this first semester where we collected *in situ* data using three sets of video camera, microphone, and laptop with screencasting software to document three different groups each week. From the subset of this data containing computational problems, we *purposefully sampled* a particularly interesting group in terms of their computational interactions, as identified by their instructor. That is, we chose our case study not based on generalizability, but rather on the group's receptive and engaging nature with the project as an *extreme case* [49].

The project that the selected group worked on for this study consists of creating a computational model to simulate the geosynchronous orbit of a satellite around Earth. In order to generate a simulation that produced the desired output, the group had to incorporate a position dependent Newtonian gravitational force and the update of momentum, using realistic numerical values. The appropriate numerical values are Googleable, though instructors encouraged groups to solve for them analytically.

This study focuses on one group in the fourth week of class (the fourth computational problem seen) consisting of four individuals: Students A, B, C, and D. The group had primary interaction with one assigned instructor. Broadly, we see a 50/50 split on gender, with one ESL international student. Student A had the most programming experience out

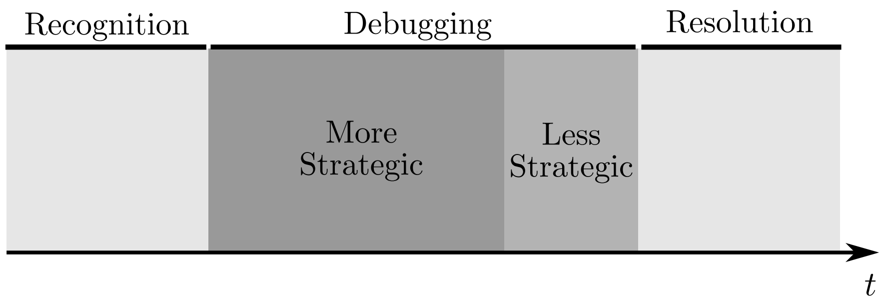


Figure 4.2: The debugging process necessarily corresponds to a phase beset on either side by the phases of recognition and resolution. Note the absence of a vertical scale, as the vertical separation merely acts to distinguish phases.

of the group. It is through the audiovisual and screencast documentation of this group's interaction with each other and with the technology available that we began our analysis.

To focus in on the group's successful physics debugging occurring over the 2 h class period, we needed to identify phases in time when the group had recognized and resolved a physics bug. These two phases in time, *bug recognition* and *bug resolution* are the necessary limits on either side of the process of *physics debugging*, as represented in Fig. 4.2. We identified these two bounding phases at around 60 minutes into the problem, and further examined the process of debugging in-between. That is, we focused on the crucial moments surrounding the final modifications that took the code from producing unexpected output to expected output.

4.1.1.1 Recognition

At around 55 min into the problem, following an intervention from their instructor, the group began to indicate that they were at an impasse:

SB: We're stuck.

SD: Yeah...

The simulation clearly displayed the trajectory of the satellite falling into the Earth not the geostationary orbit they expected as observed on the screencast. This impasse was matched with an indication that they believed the fundamental physics principles necessary to model this real world phenomenon were incorporated successfully into the code:

SB: And it's gonna be something really dumb too.

SA: That's the thing like, I don't think it's a problem with our understanding of physics, it's a problem with our understanding of Python.

Instead of attributing the unexpected output with a mistake in their understanding or encoding of the fundamental physics principles, they instead seemed to place blame on the computational aspect of the task.

During this initial phase, we see a clear indication that the group has recognized a bug – there is an unidentified error in the code, which must be found and fixed:

SA: I don't know what needs to change here...

SD: I mean, that error means we could have like anything wrong really.

Although they have identified the existence of the bug, they still are not sure how to fix it – this necessitates the process of debugging.

4.1.1.2 Physics debugging

Within the previously identified phase of bug recognition, the group developed a clear and primary task: figure out exactly how to remove the bug. Eventually, following a little off-topic discussion, the group accepted that in order to produce a simulation that generates the correct output, they must once again delve into the code to check every line:

SA: I'm just trying to break it down as much as possible so that we can find any mistakes.

In this way, the group began to not only determine the correctness of lines of code that have been added/modified, but also began to examine the relationships between those lines of code.

For example, the group began by confirming the correctness of the form of one such line of code:

SA: Final momentum equals initial momentum plus net force times delta t. True?

SC: Yeah...

SB: Yes.

SA: O.K. That's exactly what we have here. So this is not the problem. This is right.

SD: Yeah.

That is, Student A (1) read aloud and wrote down the line of code $\vec{p}_f = \vec{p}_i + \vec{F}_{\text{net}} * dt$ while the entire group confirmed on its correct form. This written line was then boxed, and was shortly followed up with (2) a similar confirmation of the line $\vec{r}_f = \vec{r}_i + \vec{v} * dt$ that immediately prompted (3) the confirmation of $\vec{v} = \vec{p}/m$. Thus, not only do we see the group determining the correctness of added/modified lines of code as in 1, 2 and 3, we further see confirmation with the links between those lines. The confirmation of the link between the lines of code 1 and 2, representing the incremental update of position and momentum in time, respectively, was evidenced not through the mere addition of the linking equation (3) to the list of lines added, but further through the gestures exhibited by student A. Pointing at (3), the $\vec{v}$ in (2), and the $\vec{p}_f$ in (1), demonstrated that the group understood that without this linking equation (3), the velocity used in (2) would not reflect the time updated velocity by means of (1).

The group ran through these types of confirmations with fundamental physics principles rapidly over the span of a few minutes. Once the group had confirmed all the added/modified lines of code to their satisfaction, the discussion quieted down. The fundamental physics principles were winnowed from the discussion, and after a little more off-topic discussion we find them seeking help from the instructor:

SD: Maybe we should just stare at him until he comes help us...

Suddenly, a haphazard change to the code:

SA: You know what, I'm gonna try something...

where Student A changed the order of magnitude of the initial momentum a few times. This modification eventually resulted in a simulation that produced the correct output.

4.1.1.3 Resolution

At about 65 min into the problem, Student A changed the order of magnitude of the momentum one final time, which produced something closer to the output that they expected:

SA: Oh wait... Oh god...

SD: Is it working?

The satellite now elliptically orbited the Earth. This marks the end of the debugging phase and the beginning of the resolution phase given that the bug had successfully been found and remedied. Given that the only line of code modified to produce this change was the initial momentum, they began to rethink the problem:

SD: I think that is the issue is that we don't have the initial momentum...

SA: Momentum correct?

That is to say, the group pursued the issue of determining the correct initial momentum with the added insight gained through debugging fundamentally correct VPython code.

4.1.2 Discussion

To summarize, in analyzing this particular group, we first identified the two phases in time when the group had recognized and resolved a physics bug. We then necessarily identified the phase in-between as the process of physics debugging in P^3, where the fundamentally correct code was taken from producing unexpected output to producing expected output. Given our assumption that the process of computer science debugging encourages desirable strategies, we then began to analyze this process of physics debugging further for strategies unique to P^3.

Given the actions exhibited during the debugging phase, we can separate them into two distinct parts: a more strategic part and a less strategic part, as shown in Fig. 4.2. The group initially gave indication that they were working in a considerate, thorough, and consistent manner, which we classify as more strategic. This is contrasted by the later indications of more haphazard actions, which we classify as less strategic. These are the two physics debugging strategies that, together, led to the resolution of the bug in this context.

The more strategic strategy was exhibited through the confirmation of individual FPPs as well as their relation to others. Not only did the group confirm through discussion, they simultaneously wrote, boxed, and referenced equations in the code – this helped to reduce the number of fundamental physics principles they needed to cognitively juggle at any given time [4]. This confirmation of FPPs through discussion presented a great learning opportunity for the entire group, where creative and conceptual differences could be jointly ironed-out. Accordingly, we tentatively refer to this strategy as self-consistency.

Although the resolution of the bug might not be tied directly to this self-consistency, that does not negate the learning opportunities afforded to the group along the way. Specifically, we saw the group double-checking every fundamental idea used and, possibly more importantly, the links between those ideas. Being physically self-consistent in this manner is a desired strategy in P^3.

The less strategic strategy was exhibited during the haphazard changes to the initial momentum. These changes to the code that eventually resolved the bug, though one of the benefits of computation (i.e., the immediacy of feedback coupled with the undo function), could have been more thoughtful. A deeper understanding of the physics or computation could have tipped the group off to the fact that the initial momentum was too small.

Again, this does not negate the learning opportunities afforded to the group through this less strategic strategy, which resembles that of ""productive messing about." [4] Accordingly, we tentatively refer to this strategy as play.

Both of these strategies identified here, self-consistency and play, provided learning opportunities to the group which are bolstered by the computational nature of the task. In other words, the necessity of translating a collection of physical ideas into lines of code which must logically flow and the benefit of immediate visual display resulted in learning opportunities which might otherwise have been missed in an analytic task. More research is needed to dissect these learning opportunities and to deepen our understanding of the strategies themselves.

4.1.3 Conclusion

This case study has described two strategies (one more and one less strategic) employed by a group of students in a physics course where students develop computational models using VPython while negotiating the meaning of fundamental physics principles. These strategies arose through the group's process of debugging a fundamentally correct program that modeled a geostationary orbit. The additional data we have collected around students' use of computation is rich, and further research is needed to advance the depth and breadth of our understanding of the myriad of ways in which students might debug computational models in physics courses.

Chapter 5

Observations

Throughout our analysis in this thesis, we have made many different types of observations, and have used those observations to help answer our research question (i.e., what are the computational practices indicative of computational thinking that are common to P^3?) . Accordingly, it is important that we take some time to elaborate on the process of and results from those observations. More specifically, in this chapter, we detail the method of our analysis (i.e., the data reduction, the coding process, and the inter-rater reliability) and illustrate the identification of some of the most interesting practices (e.g., troubleshooting and debugging, assessing computational models, and creating computational abstractions). The remaining practices are presented in Ch. 6 and Apps. A–C.

5.1 Analysis

Our full analysis involves different stages: first, the initial data was collected and subsequently reduced in order to provide a manageable set of data; next, a coding scheme was generated – using the Weintrop framework from Sec. 2.1 – to help identify computational practices; and finally, inter-raters were used to ensure the reliability of the analysis. Each of these three stages are detailed below.

5.1.1 Data reduction

Our total set or corpus of data consists of in-class video of nine groups of four individuals working. Each group works on three computational problems (twenty-seven videos in total) that increase in difficulty/complexity as the semester progresses. These computational problems, presented in Sec. 3.1, require students to construct various computational force models in code. Each week, the appropriate force model increases in complexity and generality. Specifically, the first problem involves a constant zero force, the second problem involves a constant non-zero force, and the third problem involves a non-constant force.

In order to first reduce the corpus of our data to a more focused and manageable set, we followed the suggestions of task analysis (see Sec. 2.4). That is, we paid attention to when students were making the most progress toward a solution. The frequency of independent progress being made increased as the complexity of the problem increased (i.e., students made the most independent progress on constructing the Newtonian gravitational force model). Here, we are defining "independent progress" as progress that is ultimately made by the group without any instructor intervention. We believe this rapid increase of independent progress is due, in part, to their lack of prior programming experience coming into the course. For example, on the first problem, many groups struggled with a basic calculation loop. By the time they see the third problem, they have already gained a little experience and know what to expect in the course.

Our initially reduced set of data consists of transcripts from in-class video (both side-view and overhead-view) of nine groups working on the geostationary satellite problem from Sec. 3.3. We also collected computer screencasts to capture exactly what students are doing when they type/click on their group laptop. Following the suggestions of thematic analysis

	SA	SB	SC	SD	TA
365			That's close to...		
366	Nine point eight is meters per second though...				
367			[Looks in notes]	[Looks in notes]	
368				Yeah, it's that.	
369				Gravity equals to like gravity, of gravity equals F net...	
370				Equals to gravity equals to {writes Newtonian force on whiteboard}.	
371		What's that?			
372				That's the constant of...	
373		Oh the G, yeah.			
374		six point six...			

Figure 5.1: A portion of transcript meant to highlight the indication of unspoken and inferred actions. For example, line 367 shows this group looking in their notes for an equation. The equation that they find is written down in line 370.

(see Sec. 2.5), we began with a full transcription of the in-class video. Any inaudible sections are indicated, with long pauses being indicated by ellipses (. . .). To distinguish between unspoken actions (e.g., pointing to an equation) and inferences made by the primary researcher (e.g., a group referring to a previously used equation), we follow the convention of square brackets ([]) and curly brackets ({ }), respectively. For example, Fig. 5.1 shows a portion of transcript highlighting these various indications.

Once we had reduced our data corpus to a more manageable and focused set of nine transcripts, we continued our investigation into the computational practices students were engaging in. Each transcript was read multiple times in order to generate a low-resolution but coherent picture of what each group was doing. This type of “familiarization” with the data is a crucial step as outline by Braun et. al. Ultimately, this low-resolution picture helped us to identify the off-topic and otherwise irrelevant discussion in order to remove those portions of the data from our analysis.

More specifically, each transcript was initially analyzed with an eye towards identifying discussion where students were solving the satellite problem. All other discussion then could be considered off-topic and safely discarded. For example, groups are often seen discussing homework for other classes that in no way relates to the Newtonian problem. Similarly, groups can often be seen discussing recent social events (e.g., a concert). This type of off-topic and otherwise irrelevant discussion, although important for the social cohesion of the group, can safely be discarded. In this way, we further reduce our data set by about one quarter. With each of nine transcript being about fifteen-hundred lines of speech/action, this translates to about fifteen-thousand lines of on-topic discussion for further analysis.

A closer analysis of this on-topic discussion is where we begin to more clearly define what computational practices look like within our data. This closer analysis started with the search for a number of characteristics (as described in Sec. 2.1), within the on-topic discussion. For example, the key characteristics for the practice of troubleshooting and debugging are: i) to identify and isolate an unexpected error, ii) articulate how to reproduce the error, and iii) work to systematically correct it. These characteristics, once identified, can be used to justify the classification of an excerpt as the computational practice of troubleshooting and debugging. Recall that each computational practice may be indicative of the computational thinking as described in Sec. 2.1. This justification allows us to define the computational practices we see in our data. A detailed account of this process of justification is described below, with applications to specific examples following in Sec. 5.2.

5.1.2 Coding process

In order to justify the classification of an excerpt as a particular computational practice, we started by systematically coding our data. This systematic coding process was applied to three streams of data: the side-view video, over-head video, and computer screencasts. These three streams were then used to generate three types of rationale: rationale according to the framework, rationale within an individual excerpt, and rationale beyond an individual excerpt. These three types of rationale are described in detail below.

In terms of the framework, we identified the various characteristics that manifested themselves in the actions and speech of each group and compared them to the Weintrop framework. Each practice, according to the framework, has any number (between one and seven) of related characteristics. The more related characteristics that we see in an excerpt, the more confident we are in classifying that excerpt as a particular practice. For example, "identifying an unexpected error in code" is one of the required characteristic of troubleshooting and debugging. Similarly, "working to systematically rectify the unexpected error" is clearly a related but distinct characteristic. The identification of either of these characteristics individually would be hinting at the practice of troubleshooting and debugging, but both of them simultaneously makes a stronger claim. This type of rationale can be found in Column G of Fig. 5.2.

Within an individual excerpt, we are able to focus in on what each member of the group says and does as they work toward a clear and focused goal. Any rationale of this type usually references line numbers pertaining to specific lines of speech/action within the excerpt that embodies the characteristic in question. In this way, we closely tie our rationale and the framework to the data. For example, a group might identify an unexpected error in their program and say:

SC: *(756)* Oh there it is {the error message}.

SB: *(757)* Where?

SC: *(758)* In the thing {shell} on the screen...

In this exchange, Student C has found the error message from the shell buried under a few other windows. This error message is ultimately used by the group to track down the cause of the unexpected error. In this way, we clearly see a group working to identify an unexpected error in our data. This type of rationale can be found in Column H of Fig. 5.2.

Beyond each individual excerpt (i.e., looking at each transcript as a whole), we are able to generate a low-resolution picture that captures the overarching goals that each group is working toward. This low-resolution picture helps us to contextualize each individual excerpt within the broader transcript. There are different ways to contextualize a particular excerpt of data (e.g., in the context of the group, the classroom, the university, the state, etc.), and relating it to other excerpts is one of the most important. For example, within an individual excerpt, a group might reference – without defining – an equation:

SA: *(894)* Should we try that one equation?

SB: *(895)* Yeah, I think we should do that...

SA: *(896)* Okay.

SC: *(897)* Yeah that's a good idea, let's use that one.

Using our low-resolution picture of the transcript as a whole, we can track back through time (often minutes, sometimes longer) to find out exactly what vague equation they are referencing:

SC: *(120)* How about we use the equation...

SC: *(121)* [writes GmM/r^2].

	A	B	C	D	E	F	G	H	I
	Excerpt #								
	SA	SB	SC	SD	TA	Tags	Framework	Within	Beyond
Line #	Student A speech and action.	Student B speech and action.	Student C speech and action.	Student D speech and action.	TA speech and action.	Here we classify the excerpt as a particular practice according to the Weintrop framework.	Rationale according to the framework goes here. This includes language from the definitions according to Weintrop and language used in the other two levels of rationale.	Rationale within the excerpt goes here. It usually references specific line #s.	Rationale beyond the excerpt goes here. It usually references other exerpt #s.

Figure 5.2: The template used for the coding process. Each excerpt is numbered, each line of speech/action is numbered and attributed to an individual member of the group, and the three types of rationale are used to justify the classification of a particular practice.

SC: *(122)* And then multiplied by r hat...

SD: *(123)* I dunno...

Any rationale provided at this level usually references the number of another excerpt that provides the necessary additional information. This level of rationale can be found in Column I of Fig. 5.2.

This coding process was followed for nine groups to generate about five-hundred candidate excerpts, each excerpt having multiple practices, and each practice having the three types of rationale described above. Each excerpt has anywhere from one to four possible practices identified with supporting rationale. That equates to roughly three-thousand individual justifications that must be found within our data. After concluding our inter-rater reliability, described below, we had a reduced data set of roughly one seventh the initial set.

The three types of rationale described above, though not necessarily persuasive individually, when taken together can provide a reasonable justification for the classification of an excerpt as belonging to a particular computational practice: the rationale from the framework provides incomplete but guiding definitions, the rationale within an individual excerpt ties us closely to the data and the immediate actions that a group is taking, and the rationale

Inter-Rater comments	Tag	Rationale from framework
I actually think this is an example of abstraction.	Creating computational abstractions	The group is identifying, creating, and using a computational abstraction as they work toward a goal.

Inter-Rater comments	Tag	Rationale from framework
I think I am struggling with what is meant by levels here. I see them trying to write a constant, but I don't see the larger connections.	Thinking in levels	The group has identified the different levels in a system.

Inter-Rater comments	Tag	Rationale from framework
What is abstraction? I'm not seeing it, but maybe I'm using some colloquial lens that is inappropriate.	Creating computational abstractions	The group has identified a computational abstraction as they advanced toward some goal.

Figure 5.3: Examples of the three levels of confidence are shown in green, yellow, and red to indicate high, medium, and low confidence, respectively. Each inter-rater suggestion is used to modify or solidify the level of confidence given to a particular practice.

beyond an individual excerpt helps to contextualize those immediate actions and speech.

5.1.3 Inter-rater reliability

In order to ensure not only reasonable, but also *reliable* justifications for the classification of the various computational practices within our data, we followed an iterative process of inter-rater reliability. One primary researcher was joined by three inter-raters, ensuring a robust coding process and stronger claims through iterative critique and discussion.

Initially, the data was coded by the primary researcher, relying heavily on the Weintrop framework and the qualitative methods described in Ch. 2, to generate an initial set of rationale for each candidate excerpt. This initial set of rationale for a particular excerpt, consisting of the three types of rationale described in the section above, was then taken as a

Inter-Rater Comments	Tag	Rationale from framework	Rationale within excerpt	Rationale beyond excerpt
	Troubleshooting and debugging	The group has **identified** an **unexpected problem** and working to correct it in a systematic manner.	The group has **identified** a problem through the output of VPython error shell (line 57). The **unexpected problem** is that they have defined their force as a scalar but it needs to be given a direction (line 67).	

Inter-Rater Comments	Tag	Rationale from framework	Rationale within excerpt	Rationale beyond excerpt
I think this a good example. I think you will want to have the shell output put into the example to make clear what the students recongized and what they dealt with.	Troubleshooting and debugging	The group has **identified** an **unexpected problem** and working to correct it in a systematic manner.	The group has **identified** a problem through the output of VPython error shell (line 57). The **unexpected problem** is that they have defined their force as a scalar but it needs to be given a direction (line 67).	TypeError: unsupported oeprand type(s) for +: 'vector' and 'float'

t

Figure 5.4: The initial rationale generated for an excerpt along with inter-rater suggestions and subsequent modification over time. With the addition of some requested information, the strength of the rationale was improved and the confidence was promoted from medium to high.

whole to formulate an initial level of confidence: low, medium, or high. Low confidence was usually given to excerpts containing only a few of the characteristics needed by a practice, or to excerpts where the identification of an individual characteristic was in serious question. Medium confidence was given to excerpts containing most of the characteristics required by a practice, or to excerpts where the identification of individual characteristics was probable. High confidence was given to excerpts containing all of the required characteristics for a practice, or to excerpts where the identification of each individual characteristic was self-evident. Examples of excerpts belonging to these different levels of confidence are shown in Fig. 5.3.

A subset of the data containing a variety of computational practices and levels of confidence was then shared with inter-raters, ranging from undergraduate students to professors. Each inter-rater subsequently tested the strength of our initial claims through discussion by asking questions and making suggestions. These suggestions, once mutually agreed upon, were incorporated into the rationale. For example, Fig. 5.4 shows one inter-rater asking a clarification question as to what the verbatim output of the shell in a particular excerpt was. The answer to this clarification question, though not obvious given the initial rationale, proves to be relevant and necessary to the strength of the rationale. This process of generating reliability through asking questions and making suggestions was followed iteratively to further strengthen each claim.

5.2 Computational practices

By analyzing all of the data with the methods described above, we have identified a number of practices that show up in our data. These practices and their frequencies within our data are summarized in Fig. 5.5. In total, we identified roughly 300 occurrences of individual practices, with some practices occurring frequently and some occurring never. The most frequent practices, though found within our data, can be expected to arise just as frequently in sufficiently similar classrooms and deserve a fair amount of attention.

The remainder of this section provides concrete examples of some of the most frequent computational practices that we found in our data. We are focusing on those practices that occur with high frequency within one group or occur with moderate frequency across multiple groups. These practices are (in no particular order): creating and analyzing data within the data practices; designing, constructing, and assessing computational models within the modeling and simulation practices; programming, creating abstractions, and troubleshooting and debugging in the computational problem solving practices; and thinking in levels and communicating information within the systems thinking practices.

Data	**86**
Collecting data	0
Creating data	27
Manipulating data	0
Analyzing data	31
Visualizing data	36
Modeling and simulation	**97**
Designing computational models	32
Constructing computational models	18
Assessing computational models	27
Using computational models to find and test solutions	13
Using computational models to understand a concept	7
Computational problem solving	**67**
Preparing problems for computational solutions	0
Choosing effective computational tools	0
Assessing different approaches/solutions to a problem	9
Creating computational abstractions	22
Developing modular computational solutions	0
Programming	21
Troubleshooting and debugging	24
Systems thinking	**67**
Defining systems and managing complexity	0
Investigating a complex system as a whole	13
Understanding the relationships within a system	13
Thinking in levels	18
Communicating information about a system	23

Figure 5.5: The frequency of each practice that was found within our unique data set.

Characteristic	Qualities
Automating	The data that is being created should be done so in an automatic or algorithmic manner. For example, an Euler-Cromer style integration is frequently used to generate large sets of numerical data representing various physical phenomena in time.
Advancing	Each group should ultimately be advancing toward completion of the specified task. For example, creating an algorithm that generates the various momenta of the satellite can ultimately be used to help generate a simulation of its trajectory.

Table 5.1: The characteristics and associated qualities pertaining to the computational practice of creating data: automating the creation of data that helps to advance toward goals.

Although the examples that follow are meant to clearly illustrate some of the common computational practices that we have observed, they do not come without their own limitations. Accordingly, Ch. 6 provides a discussion of those limitations, as well as presents some of the less common and unobserved practices.

5.2.1 Creating data

The computational practice of creating data, as defined by Weintrop et. al, involves the generation (as opposed to the collection) of computer data while "investigating phenomena that cannot be easily observed or measured or that are more theoretical in nature." This type of data creation frequently arises in physics and engineering given that data collection is infeasible in many realistic situations. For example, complex computer models can be used to generate data that can be used to optimize launch conditions for satellites and manned rockets when real-world collection of data is too costly or dangerous. The fundamental characteristics associated with this practice, as summarized in Tab. 5.1, are: i) defining a computational procedure that automatically/algorithmically creates data and ii) using that procedure or the resulting data to advance the overall goals of the task.

Consider Excerpt 9 from Group H. Over the course of two hours, this group can be seen ensuring that their MWP will dynamically update the position of the satellite. This entails ensuring that the momentum of the satellite will also dynamically update. Accordingly, the group works to construct a computational algorithm that will automatically create sets of data representing the position and momentum of the satellite over time. These sets of data are then ultimately used to advance toward completing the goal of producing of a realistic visualization of the trajectory of the satellite.

Early on, the group can be seen discussing their goal of generating a visualization of the satellite's orbit (lines 195-196). They consider changing the initial position of the satellite (line 199) to what they calculated from the previous problem:

SD: *(195)* So, it's mostly just trying to figure out how to get it {the program} to display an orbit...

SA: *(196)* Yeah, it is.

SC: *(197)* Wait, we have to change the position, don't we?

SB: *(198)* I think the initial position stays there, we have to update position though...

SC: *(199)* Yeah, we have to change the initial position to what we found... it was this far away, you know?

SA: *(200)* Yeah.

SB: *(201)* Yeah.

SA: *(202)* Which was... four point four two times ten to the seven.

SB: *(203)* Four point two... [codes]

They make the distinction between changing the initial position of the satellite and changing the way that the position updates over time (line 198). This is an important distinction because each change involves vastly different amounts work to accomplish, and only one results in the automatic/algorithmic creation of data. That is, changing the initial position of the satellite is a simple change of a numerical value, whereas changing the way that the position updates over time involves defining a set of algorithms with multiple variables inside of the calculation loop. Ensuring that the position updates properly is a big advancement toward their goal of producing a realistic visualization.

Eventually, they propose an Euler-Cromer style algorithm to automatically update the position of the satellite (line 222) in terms of its momentum, mass, and time:

SB: *(217)* Alright...

SB: *(218)* Okay, so we have to add its new position.

SA: *(219)* But it has to update its position every time...

SB: *(220)* Right.

SA: *(221)* So we have to make it update.

SB: *(222)* Satellite position plus momentum of the satellite...

SA: *(223)* Over the mass?

SB: *(224)* Times the change in time... yeah so it's, yeah.

SB: *(225)* But the momentum is always changing...

Although the group has clearly laid out the way that the position of the satellite will need to change (line 222), they have raised another concern in terms of the momentum of the satellite (line 225). In other words, they have defined a procedure to automatically calculate the positions of the satellite, but still need to define a procedure to automatically calculate the momenta.

Later, as the group works toward defining a procedure to change the momentum of the satellite over time, they recall the concept of both iterative prediction (line 684) and Newton's second law (line 695) from the notes:

SB: *(681)* So we gotta figure out how to change the momentum in there {the code}.

SB: *(682)* What was the equation from last week?

SA: *(683)* Umm... F grav... No.

SD: *(684)* What about using iterative prediction for like future positions?

SD: *(686)* Right?

SC: *(687)* The change in momentum would be the net force times...

SB: *(688)* Because the force is mass times acceleration...

SC: *(689)* That would be it, yeah.

SB: *(690)* So integrate that.

SC: *(692)* Changing momentum is force times change in time...

SB: *(693)* Oh, there we go, nice.

SA: *(694)* Wait what is it?

SB: *(695)* The change in momentum is the net force times change in time.

With these two algorithms defined, their MWP is ready to automatically and dynamically update the position and momentum of the satellite. Afterward, the group spends a fair amount of time incorporating the appropriate force model into their code. The construction of these algorithms, along with the correct force model, shows a clear advancement toward their goal (line 195) of generating a visualization of the satellite's orbit.

To summarize, the group can be seen *automating* the generation of sets of data representing the position and momentum of the satellite over time. Further, with these sets of data, the group is ultimately *advancing* their progress toward producing a visualization of orbital motion. Given the identification of these two characteristics, we classify this excerpt as the computational practice of creating data.

5.2.2 Analyzing data

The computational practice of analyzing data, as defined by Weintrop et. al, usually involves large sets of data (that have either been created or collected) where groups are "looking for patterns or anomalies, defining rules to categorize, and identifying trends and correlations." This type of analysis shows up frequently within the field of physics, especially given the computational nature of many (if not most) modern investigations. For example, extremely large sets of data are generated while investigating the formation and evolution of galaxies throughout the universe. Being able to effectively analyze a large set of data is a crucial skill within many interdisciplinary fields. The fundamental characteristics associated with this computational practice, as summarized in Tab. 5.2, are: i) a general process of analysis (detailed in Tab. 5.2) and ii) a conclusion being drawn based on that analysis.

Consider Excerpt 35 from Group H. Overall, this group can be seen engaging in the process of analysis of a set of data that represents the net force acting on the satellite, and

Characteristic	Qualities
Analyzing	This is a broad term that usually involves at least one of many types of analysis. For example, sorting a set of data into different categories, looking for trends or patterns within a given set, looking for correlations between multiple sets, and/or identifying outliers and anomalies are all considered to be different types of analysis.
Concluding	The information (e.g., a pattern or trend) gathered from the analysis of a set of data should ultimately be used to make or draw some conclusion. This characteristic, though an important one, is not necessarily required for a group to be analyzing data.

Table 5.2: The characteristics and associated qualities pertaining to the computational practice of analyzing data: a general process of analysis leading to conclusions based on evidence.

drawing a conclusion based on the results of that analysis. The particular process of analysis observed in this excerpt involves both categorization and patterning. The categories that the data are placed in are: a) large-scale numbers and b) vector quantities. The trend that the group recognizes is that the set of data representing the net force is time dependent.

Prior to the beginning of this excerpt, the group adds a print statement (i.e., `print(Fnet)`) into their calculation loop to print off the numerical values (x-, y-, and z-components) of the net force acting on the satellite over time. They do this to check that their model is producing the expected values:

SD: *(1330)* How many times does this calculation loop run through?

SB: *(1331)* A lot...

SD: *(1332)* Yeah.. a lot [looking at the output].

SB: *(1333)* However many seconds are in a day.

SA: *(1334)* Eighty six thousand.

SD: *(1335)* Wow...

SB: *(1336)* Yeah doing it line by line is not gonna be easy.

With this print statement, they are creating a large set of data (line 1332) that is subsequently analyzed.

The group confirms that their print statement is displaying a large set of data that represents the net force on the satellite (line 1338). At the same time, they begin to categorize the data and look for trends:

SD: *(1337)* It's not showing the satellite because I think the {window} scale is too small.

SD: *(1338)* But it's outputting all of the forces, and it is...

SD: *(1339)* It's changing too I think.

SB: *(1340)* How big are they?

SB: *(1341)* I'm assuming were talking about F grav...

SC: *(1342)* Yeah, it is big.

One trend that the group suggests (line 1339) is that the values in the set have some sort of time dependence. Similarly, one category that the group places the data in (line 1342) is that of having a large order of magnitude – which is expected given the type of force that they are analyzing.

Mistakenly, the group believes that the trend of time dependence that they have identified in their data is not the expected or desired one. In other words, they suggest that the set of data should be constant in time (line 1343):

SB: *(1343)* Uhh... I don't think it's supposed to be changing.

SB: *(1344)* Not a good sign.

SB: *(1345)* Do we have it as a vector or a scalar right now?

SD: *(1346)* Right now we have it as a vector.

Additionally, the group further categorizes the set of data as being a collection of vectors as opposed to a collection of scalars (line 1346). This focus on the vectorial nature of the net force ultimately helps them to draw a conclusion about how it should behave as the satellite changes position.

After a little off-topic discussion, the group begins to consider how the various components of the net force should not only change in time (line 1425), but should also remain a particular size (line 1434):

SB: *(1420)* We need F grav to be a vector.

SD: *(1421)* We have it as a vector... it is a vector right now.

SB: *(1422)* How?

SA: *(1423)* How do you have it as a vector?

SD: *(1424)* I initiated it as a vector.

SB: *(1425)* Right, but it needs to move.

SD: *(1426)* Oh, does it have to be negative?

SB: *(1427)* Either way, it has to be in the x and the y direction...

SD: *(1428)* Oh well then you just do this [adds the force for the x-component]...

SB: *(1429)* Because... But it's the components that would make F grav bigger than we need it to be?

SD: *(1430)* Why?

SB: *(1431)* Because a component vector... If we have one like that [draws a vector toward the fourth quadrant] then it's gonna be out to there...

SC: *(1432)* No, it would be double.

SB: *(1433)* Right it would be that long.

SB: *(1434)* And we just need it to be that long.

SD: *(1435)* So just divide it by two then?

SB: *(1436)* Except it changes in time...

SB: *(1437)* Because when it's right here, it's only going down, and when it's right here it's only going across...

SB: *(1438)* But when it's right here, it's going down and across...

SC: *(1439)* Yeah.

In other words, although the net force has been initiated as a vector, it has been initiated as a constant vector (pointing only in the y-direction). The group reaches the conclusion (line 1437) that the force must be modified so that it can change directions depending on where the satellite is located relative to the Earth. Furthermore, they conclude that it is important that magnitude of the net force remain a constant (line 1434). These conclusions ultimately lead them to rethink their force model.

To summarize, this group can be seen *analyzing* a set of data representing the net force acting on the satellite over time. They have identified the *trend* that the data changes over time, and the data were placed in the *categories* of being large-scale numbers and being vectors quantities. The *conclusion* that the group makes is that the net force should not only be a vector, but that its components should be able to oscillate between the x- and y-components depending on where the satellite is. Given this process of analysis and the conclusions being drawn, this excerpt is thought to illustrate the computational practice of analyzing data.

5.2.3 Designing models

The computational practice of designing computational models, as defined by Weintrop et. al, involves the process of making "technological, methodological, and conceptual decisions." These types of decisions are frequently dealt with in the STEM discipline given the complexity of modern scientific endeavors. Scientific rigor and sound methodology must be maintained while using tools at the forefront of technology (i.e., computation) to investigate modern phenomena. At the same time, developing a deep conceptual understanding of the models and the phenomena that they represent is playing an increasingly important role in the sharing and communication of scientific information. Accordingly, the fundamental characteristics associated with this computational practice, as summarized in Tab. 5.3, are: i) defining the components of a model, ii) describing how the components of the model interact, and iii) articulating what predictions can be made with the model. In keeping with the recent literature on modeling in education research, we limit our investigation to models pertaining to the force acting on the satellite (e.g., a local gravitational force model or a Newtonian gravitational force model).

Consider Excerpt 11 from Group B. Throughout this excerpt, the group can be seen working to incorporate a centripetal force model (i.e., $\vec{F}_{\text{cent}} = -\frac{mv^2}{R}\langle\cos\theta, \sin\theta, 0\rangle$) into

Characteristic	Qualities
Defining	Each individual component of a model must be separately defined in code. For example, the mass of an object and the local acceleration due to a planet can be separately defined and used to construct the corresponding local gravitational force.
Relating	The group must describe the way that the individual components of the model relate to the phenomenon that is being studied. This relationship usually mirrors an equation or an expected type of behavior. For example, the Newtonian gravitational force follows an inverse square position-dependence.
Predicting	The group must articulate what information their model will provide them, and use that information to make predictions about the time evolution of a phenomenon given initial conditions. For example, a force model can generate the various values of the force acting on an object at different positions in time. This set of data can then be used to make predictions about the motion of the object.

Table 5.3: The characteristics and associated qualities pertaining to the computational practice of designing a computational model: defining components, relating them to one another, and using them to make predictions.

their code. Ultimately, the group is dissuaded from using this particular model through discussion with the TA. Nevertheless, this excerpt is a clear illustration of the practice of designing a computational model.

A few minutes into beginning the problem, the group has recognized that they need to use a force model (line 118) to calculate the trajectory of the satellite, as opposed to just plotting it using the expected radius (line 116):

SA: *(111)* Now were saying that it's {the radius} a variable...

SA: *(112)* So what do we want to do with this other number?

SB: *(113)* Well, you said the radius from here to here is not gonna be the same as from here to here?

SA: *(114)* Yeah.

SB: *(115)* Well, should we... Could we Google how, like how much farther or shorter it is from here to here?

SD: *(116)* Okay, I think actually what it's trying to get us to say is that we can't just plot its path around by using the radius of the orbit...

SA: *(117)* Right.

SD: *(118)* We have to actually use the force that is acting on it to find it's path.

SA: *(119)* We have to use the force.

SD: *(120)* We have to use the force.

The group has begun to articulate the information that their model will provide them, even if they have not yet decided on the particular model. In other words, their force model will allow them to make predictions about the position and trajectory of the satellite.

After a little off-topic discussion, the group decides on a particular force model to use:

SD: *(152)* The force is like v squared... The force is uhh v squared times m over the radius of orbit.

SD: *(153)* Correct me if I'm wrong...

SA: *(154)* Sorry?

SD: *(155)* The force is equal to mass times v squared over the radius of the orbit.

SB: *(156)* So maybe we could just find it {the force} at that distance?

SD: *(157)* Well, we have access to a variable that represents our radius of orbit...

SB: *(158)* And we have mass.

SD: *(159)* And we have mass.

SC: *(160)* We found the velocity last time...

SB: *(161)* And we know the radius and know the velocity.

SB: *(162)* So we can just find the net force.

Here, the group is clearly identifying the individual components of the centripetal force model (lines 157-161) and making sure that they are separately defined in code. Additionally, they have identified a clear mathematical relationship between them (line 152) that they recall from memory.

Before jumping into the construction of the newly proposed model, they spend a little time discussing its behavior and how it relates to the phenomenon:

SD: *(182)* If we could get it {the force} to oscillate between maximums we could get a rotation...

SD: *(183)* But how do we represent that as a force... Because it's obvious that they want us to do that.

SA: *(184)* Sine and cosine?

SD: *(185)* Sine and cosine?

SA: *(186)* If we do sine and cosine, if we have both of them, one in the x, one in the y, like this [points to notes] is saying...

SA: *(187)* Then even if one goes to zero, like you were saying, then the other one is gonna be close to one.

SA: *(188)* And so...

SD: *(189)* We have to use our angles?

SC: *(190)* Ohhh...

SD: *(191)* And we have access to angles that are defined below.

SD: *(192)* Oh my god, that's so great, that's perfect, you're totally right.

Specifically, they articulate the way that the components of their force model will need to oscillate to cause a rotation (line 182). This oscillatory behavior has a direct relation to the mathematical sine and cosine functions that they plan to use (line 184) – as one component approaches a value of zero, the other component will approach a value of one (line 187). They also identify yet another individual component of their model (line 191) with the angle of the satellite.

To summarize, the group begins by recognizing that using a force model will allow them to *predict* the trajectory of the satellite in a more general way (line 118). After deciding on a centripetal force model, they then separately *define* the individual components of the mass, velocity, radius, and angle of the satellite (lines 157-161 and 191). Finally, they *relate* the sinusoidal nature of the model to the expected sinusoidal behavior of the satellite's trajectory (lines 182 and 186). Given these three characteristics, this excerpt is a clear illustration of the computational practice of designing a model.

5.2.4 Assessing models

The computational practice of assessing a computational model, as defined by Weintrop et. al, involves "understanding how the model relates to the phenomenon being represented."

Characteristic	Qualities
Assuming	In designing a computational model, certain assumptions are invariably taken into account. These assumptions – regardless of how appropriate or valid – should be identified and clearly articulated by the group. For example, the assumption that the satellite will always be traveling in a perfectly circular orbit, although a poor one, is still an assumption.
Validating	As more assumptions are built into a model, its validity should continually be checked to ensure its predictive accuracy. For example, assuming that an orbiting satellite is acted on by a constant net force is not valid for long periods of time.

Table 5.4: The characteristics and associated qualities pertaining to the computational practice of assessing a computational model: identifying assumptions and validating them.

This is a crucial step in the process of modeling – without an assessment of the validity and meaning of the results (i.e., without a deep understanding), the model is almost certainly useless. The fundamental characteristics associated with this crucial computational practice, as summarized in Tab. 5.4, are: i) identifying assumptions built into the model and ii) validating the model. These two characteristics, if confidently observed within an excerpt, would serve to classify that excerpt as the computational practice of assessing a computational model.

Consider Excerpt 9 of Group C. Generally speaking, the group can be seen working to incorporate a gravitational force into their code. Early on, they recognize that their code is missing the net force on the satellite, and subsequently spend about thirty minutes deciding if and how they should should incorporate one. Eventually, they reach a conclusion to add a gravitational force based on their assessment of a couple of different models (i.e., a local gravitational force and a Newtonian gravitational force).

A few minutes into the problem, the group considers what happens to the initial momentum of the satellite as their program runs (line 256):

SA: *(253)* Umm...

SB: *(254)* Okay.

SA: *(255)* So that's our initial momentum.

SA: *(256)* And then what happens {to the momentum}?

SD: *(257)* And then...

SA: *(258)* We need, we have it...

SA: *(259)* The net force equation is what's wrong...

SD: *(260)* Yeah and the net force equals to like gravity, right?

Obviously the group is concerned with the state of the net force equation (line 259), and a proposal is made to set the net force equal some sort of gravitational force (line 260). This is the beginning of the assessment of their net force model.

They continue to discuss and validate the type of gravitational force that they plan to incorporate into their code. Specifically they wonder what numerical value they should be using (line 262), and they suggest using the local gravitational constant ($g = 9.81\,\mathrm{m/s^2}$):

SD: *(261)* So we just need to like plug in the value of gravity right?

SA: *(262)* Yeah... but what's the value that we need?

SA: *(263)* Because we have um... we have um... we have...

SA: *(264)* Mass in kilograms and we have the radius of orbit in kilometers, obviously we all know like nine point eight number...

SC: *(265)* That's only close to the surface of the Earth...

SA: *(266)* Nine point is meters per second though...

However, they recognizes that their satellite is not particularly close to the surface of the Earth (line 265), and that the local gravitational constant is not particularly valid at the actual distance. In other words, the group can be seen validating their computational model based on the particular situation.

Eventually, the group does decide on a particular gravitational force to use (line 270):

SC: *(267)* [looks in notes]

SD: *(268)* Yeah it's that [points to equation].

SD: *(269)* Gravity equals to like gravity, of gravity equals F net...

SD: *(270)* Equals to gravity equals to [writes Newtonian force on board]...

SB: *(271)* What's that?

SD: *(272)* That's the constant of...

SB: *(273)* Oh the G yeah.

SB: *(274)* Six point six...

This force involves the universal gravitational constant ($G = 6.61 \times 10^{-11}\,\mathrm{N\,m^2/kg^2}$) as opposed to the local gravitational constant, which they clearly state (line 273). Again, the group has ensured the validity of their net force model by assessing the location of the satellite and subsequently using the appropriate gravitational constant.

Before getting to far, the group takes some time to clearly articulate an assumption (line 275) built into their model:

SA: *(275)* Sorry i just wanted to write here that we're making an assumption [writes on WB].

SD: *(276)* Yes.

SD: *(277)* F net equals to gravity.

SD: *(278)* Yes.

SD: *(279)* Equals to...

SA: *(280)* I just did that [adding an E] to show that that's of the Earth.

SA: *(281)* Does everyone agree that this is an assumption?

SC: *(282)* Yeah.

The fact that the only force acting on the satellite is a gravitational force is really just an assumption (although a good one) made at this point. The group specifically takes the time to articulate and agree upon this important assumption.

To summarize, this excerpt demonstrates two fundamental characteristics: the group is *validating* their model when they compare which gravitational force/constant they should be using, and the group is *assuming* things about their model when they say that the net force is comprised of only a gravitational force. Given these two characteristics, we feel confident in categorizing this excerpt as a strong illustration of the computational practice of assessing a computational model.

Characteristic	Qualities
Conceptualizing	There needs to be some concept that a group is focusing on. Concepts usually range from individual physical quantities to more complicated physical relationships.
Representing	A particular concept should be represented mathematically. This process of representation usually involves translating a mathematical equation from the notes into a more general computer function.

Table 5.5: The characteristics and associated qualities pertaining to the computational practice of creating computational abstractions: representing physical concepts.

5.2.5 Creating abstractions

The computational practice of creating abstractions, as defined by Weintrop et. al, requires "the ability to conceptualize and then represent an idea or a process in more general terms." This ability show up frequently in the STEM domains – especially within introductory computational physics. The two fundamental characteristics of this computational practice, as summarized in Tab. 5.5, are: i) conceptualizing an idea and ii) representing it in more general terms. These two characteristics, if confidently observed within an excerpt, would serve to classify that excerpt as the computational practice of creating computational abstractions.

Consider Excerpt 13 from Group D in the following analysis. Overall, the group can be seen giving their net force a direction through the use of a unit vector ($\hat{r}$). They first recognize that their force needs to be a vector, and propose an equation to use that specifically involves a direction ($\vec{F} \propto \hat{r}/r^2$). Once they have their equation to work with, they begin to discuss how they can define it as a general function. In other words, the group can be seen *conceptualizing* and *representing* an idea in general terms.

They start by looking for an equation that they can use to try to calculate the net force on the satellite:

SA: *(108)* [calculating the magnitude of the force on his calculator]

SC: *(109)* Yeah just try that one equation first.

SC: *(110)* If that's not gonna work, then {I} think {the} other...

SD: *(111)* But the direction of F is {a vector}...

SD: *(112)* So we need to turn the r into a vector.

SC: *(113)* I think we should...

SD: *(114)* [writes force equation with $\hat{r}$]

Here the group can be seen deciding (or at least suggesting in line 109) that the computational force model that they are using will need to take a direction into account (i.e., it needs to be a vector). This equation, $\vec{F} \propto \hat{r}/r^2$ (retrieved from their notes), is written down on the WB. Notice that it involves using $\hat{r}$ to give the force a direction. This unit vector is the computational abstraction that the group identifies and ultimately begins to construct in their program. This abstraction helps them to work toward their goal of constructing the non-constant Newtonian gravitational force on the satellite.

Once the unit vector ($\hat{r}$) has been identified as a computational abstraction, they begin its creation in code:

SD: *(115)* So just put the r value, vector value...

SD: *(116)* Just put this [points to r hat] uhh function...

SB: *(117)* As a parameter?

SD: *(118)* Just give the computer a function so we don't have to calculate F like SA is doing.

SB: *(119)* That's a good idea.

Although they are clearly focusing on the concept of the direction of the Newtonian gravitational force, they are a little stuck on how to actually go about creating it. However, they at least know that they want it to be a function (line 118) rather than just a constant numerical value. Presumably, this is because they know that the numerical values will need to change in time (line 271):

SD: *(269)* No I mean this is the distance... and it has a direction...

SB: *(270)* So it's a vector.

SD: *(271)* Yeah this the position of the satellite is a vector.

SD: *(272)* Change with time...

SC: *(273)* Yeah I'm talk about the very beginning with the D... here [points to WB].

SB: *(274)* So the D is the radius...

To summarize this excerpt, the computational abstraction that the group has created is a function for the unit vector of the position of the satellite (line 116). They decide to create a function (as opposed to a hard-coded value) so that it will be able to change over time (line 272). That is, the group has *conceptualized* the direction of the force with a unit vector ($\vec{F} \propto \hat{r}$) and have *represented* that idea as position dependent and therefore more generalizable function (`rhat = satellite.pos/R`). Given these characteristics, this excerpt illustrates the computational practice of creating computational abstractions.

Characteristic	Qualities
Isolating	The cause of an unexpected error that arises in a program must be tracked down. This sometimes involves retracing steps (or keystrokes) through the undo command, but usually involves testing the program through a process of guessing and checking.
Correcting	The unexpected error must ultimately be corrected in a long-term and generalizable manner.
Systematizing	When isolating or correcting the unexpected error, it should be done is a systematic and efficient way. This characteristic is not necessarily required.

Table 5.6: The characteristics and associated qualities pertaining to the computational practice of troubleshooting and debugging: isolating an unexpected error and correcting it in a systematic manner.

5.2.6 Troubleshooting and debugging

The computational practice of troubleshooting and debugging, as broadly defined by Weintrop et. al, refers to "the process of figuring out why something is not working or behaving as expected." This process is frequently undertaken by students in all fields of study – especially within introductory computational physics, given their reliance on incomplete/approximate computational and physical models. The three fundamental characteristics of this computational practice that we have identified, as summarized in Tab. 5.6, are: i) isolating an unexpected error, ii) correcting that unexpected error, and iii) doing so in a systematic/efficient way. These three characteristics, if confidently observed within an excerpt, would serve to classify that excerpt as troubleshooting and debugging.

For example, consider Excerpt 2 from Group I in the following analysis. Broadly, the group can be seen working to incorporate realistic values and generalizable functions into their MWP. A couple of minutes into starting the problem (Sec. 3.3), they modify the prewritten numerical value for the mass of the satellite from `1` to `1E4`. This leads, over the course of about thirty minutes, to the group defining the momentum of the satellite as a function.

That is, the group can be seen *isolating* the cause of an unrealistic satellite trajectory and ultimately *correcting* it in a *systematic way* by redefining the momentum of the satellite from a hard-coded value to computer function.

The group begins by reading through the Euler-Cromer update of the position of the satellite in the calculation loop (line 6). This update involves the position of the satellite, the momentum of the satellite, the mass of the satellite, and the discrete time step (i.e., `satellite.pos = satellite.pos + satellite.p/msatellite*dt`):

SC: *(6)* It {the MWP} does the satellites position plus, vector, zero, five thousand, zero, thats the momentum of the satellite...

SC: *(7)* Divided by the mass, so, satellites position...

They also begin to consider the numerical values that have been assigned to the physical quantities being used (i.e., the initial position and momentum of the satellite and the mass of the satellite). Notably, the group points out (line 8) that the mass of the satellite should be changed to reflect the realistic value given in the problem statement:

SD: *(8)* This [points to the screen] is the mass? should we change that then?

SC: *(9)* Yeah we know that this is... they gave it to us didn't they?

SD: *(10)* Fifteen times ten to the third [reading from the problem statement].

SA: *(11)* I have all of the numbers up here [points to 4Q].

SC: *(12)* [changes the mass of the satellite from 1 to 1.5E4]

By changing the mass of the satellite from `1` to `1.5E4` (line 12), they have correctly modified the program to reflect the realistic situation presented to them. However, by changing the mass of the satellite they have also introduced an unexpected error – their satellite looks as if it is floating motionless in space.

After making their change to the program (line 12), the group begins to wonder (line 15) what the new visualization will look like. After some back and forth about what the visualization used to look like (line 18), they decide to run the program and observe the new visualization. The group discovers (line 20) that the satellite, although it used to travel in a straight line trajectory, now remains stationary relative to the rotating Earth:

SA: *(15)* Well I wonder what it {the visualization} looks like now...

SD: *(16)* It just like shoots straight.

SA: *(17)* Are you {sure}, did you already try it?

SC: *(18)* Yeah {previously}, but it might be different...

SD: *(19)* We just changed the mass.

SC: *(12)* [runs the program]

SA: *(20)* Uhh its not moving, maybe we should...

Given this unexpected error, the group begins to isolate the cause of the unexpected error. They consider that they may have introduced a syntax error since they last ran the program (e.g., in using E as opposed to **), resulting in it crashing the program (line 22). They also consider that changing the mass might have lead to the unexpected error, and work to at least temporarily rectify it (line 25):

SC: *(21)* We probably wrote it wrong...

SC: *(22)* Maybe it might have crashed the...

SA: *(23)* Well just exit out then.

SD: *(24)* Yeah.

SD: *(25)* Should we change it back and see if it runs again?

SC: *(26)* Well if we change it back to one it'll probably run again because we didn't change anything else.

SA: *(27)* Well can I see what it looks like when it runs with one?

SC: *(28)* Yeah.

Changing the mass of the satellite back to its initial dummy value is indeed a temporary fix to their unexpected error. However, a more long-term correction is needed to ensure the generalizability of their program. Ultimately, the group does work to correct the error in a more systematic and long-term manner:

SB: *(745)* So, okay so, we're all in understanding of why we are doing it like this {defining the momentum of the satellite as the mass times velocity} instead of declaring this {a hard-coded numerical value}?

SB: *(746)* It also like it makes it really explicit too, like when we go down here and do this thing where you take p divided by m you are literally just left with velocity...

SB: *(747)* So that's good.

SD: *(748)* Yeah.

Here, the group recognizes that the momentum of the satellite should be defined as a function utilizing the velocity and mass of the satellite separately (line 745). That way, when the momentum is used in the Euler-Cromer update, it will correctly divide out the mass no matter what value they use (line 746).

The type of systematic correction of an unexpected error seen in this excerpt can be contrasted with our motivating case study (Sec. 4). That is, the changes that the group made in the case study could be characterized as a more haphazard approach, as opposed to the present excerpt where the group shows a certain level of reasoning behind their actions (line 746). Accordingly, this excerpt seems to illustrate a group working in a systematic/efficient way as they troubleshoot and debug their program.

To summarize, the unexpected error that the group runs into is that in changing the mass of the satellite to reflect the realistic situation, the satellite remains motionless relative to the rotating Earth (line 20). This introduces concern to the group, presumably because a straight line trajectory is closer to a geostationary orbit as compared to no trajectory at all. The group works to *isolate* the error by changing the mass of the satellite back to its initial dummy value and finding that this does indeed rectify the unexpected error (line 25). Ultimately, the group works to *correct* this error first temporarily by changing the mass of the satellite, and then more *systematically* and permanently by redefining the momentum of the satellite as a function (line 745). Given these characteristics, this excerpt illustrates the computational practice and process of troubleshooting and debugging.

5.2.7 Thinking in levels

The computational practice of thinking in levels, as defined by Weintrop et. al, involves the analysis of a system that ranges "from a micro-level view that considers the smallest elements of the system to a macro-level view that considers the system as a whole." This type of high- and low-resolution analysis of a system is a skill that shows up frequently in scientific

Characteristic	Qualities
Leveling	A group should either implicitly or explicitly define the different levels of a system. For example, every MWP can be broken down into an initial condition level and a calculation loop level.
Featuring	The unique features of each level should be articulated by the group. For example, a group might articulate that physical quantities that need to change in time must be placed in the calculation loop.

Table 5.7: The characteristics and associated qualities pertaining to the computational practice of thinking in levels: breaking a program into different levels and attributing features to them.

disciplines – and especially within the domain of computer science. The various control structures common to computer programming (e.g., a while or a for loop) must not only work independently (i.e., at the micro-level) but must also work together (i.e., at the macro-level) with other control structures to produce the desired results of the program. Accordingly, the two fundamental characteristics that we have identified for this computational practice, as summarized in Tab. 5.7, are: i) identifying the different levels of a system and ii) correctly attributing features of that system to the appropriate level.

For example, consider Excerpt 6 from Group A in the following analysis. Broadly speaking, this excerpt focuses on the group making decisions about what needs to be added to their code and, more importantly, where those things needs to be added. More specifically, they work to construct a function for the momentum of the satellite (which depends on its velocity) as well the net force acting on it.

Early on, the group decides that they should construct a function for the momentum of the satellite in their program (line 76):

SC: *(74)* Umm, so we have like it's defining p of the satellite, and that's like p is momentum you know? Like p equals m v.

SC: *(75)* But there's nothing in here that actually defines the p of the satellite as being m v.

SC: *(76)* So I feel like we need to put in a v, and then the velocity of the satellite is a variable.

SC: *(77)* And then make the momentum of the satellite as a combination of the mass and velocity...

SB: *(78)* Umm, my question for you, from the perspective of...

SB: *(79)* We're doing circular motion, and as you go around from point a to b, your velocity is changing cause it's changing direction

SB: *(80)* Maybe, I guess we can define speed, but uhh the trick with velocity... since it's going to be changing.

SB: *(81)* Like you want the variable to continue changing...

SB: *(82)* And for the variable to continue updating you have to put it in the calculation loop...

SC: *(83)* Umm, okay.

However, this raises the issue of where to actually place the function in the code (line 78). The group decides that they must define the velocity inside the calculation loop (line 82) given that it must "continue updating" as its direction continues to change. The crucial feature that the group is articulating here is that the calculation loop is where time-dependent or changing quantities must be placed.

After a short TA interaction focusing on the generalizability of their program, the group returns to topic of where certain things are/should be placed in their code:

SB: *(107)* May I umm, may I uhh...

SB: *(108)* Okay so, there is like, there's two sections in the code...

SB: *(109)* So in the code, you have your calculation loop and your parameters and initial conditions.

SB: *(110)* So from what we have, we're defining our initial conditions as this model right here, which is just Earth and the satellite, like it's defined these two bodies and it has set the momentum of this...

SB: *(111)* And then I was thinking, in the code here in the calculation loop the force is set to zero zero zero, so were never defining F net at any point.

SB: *(112)* I think what we need to do is describe F net. The only other thing we have to declare is the radius.

SC: *(113)* Yeah, sure, we could do that.

SD: *(114)* Okay.

Here, the group clearly articulates (line 108) the two different sections/levels of the program (i.e., the initial conditions and the calculation loop) and details some of the components belonging to each level. That is, the objects of the Earth and the satellite belong to the initial conditions (line 110) and the net force acting on the satellite belongs to the calculation loop (line 111).

To summarize, the group has broken their program into the two different *levels* of initial conditions and calculation loop (line 108). Similarly, they have attributed the particular

Characteristic	Qualities
Communicating	The act of communication can range from pure dialogue between two or more individuals to detailed visualizations that capture the relevant information to be shared. For example, creating a graph of a physical quantity vs. time can be used to succinctly share information about the time dependence of that physical quantity. Alternatively, this time dependence could be articulated verbally through dialogue.
Understanding	The information being communicated should demonstrate an understanding that the group has of the underlying mechanics. For example, a group might communicate the way that the position, force, and momentum of the satellite are interrelated as simulated time progresses.

Table 5.8: The characteristics and associated qualities pertaining to the computational practice of communicating information: a general process of communication that demonstrates an understanding.

feature of time-dependence to the calculation loop (line 82). Given these two characteristics, this excerpt is can be used to illustrate the computational practice of thinking in levels.

5.2.8 Communicating information

The computational practice of communicating information, according to Weintrop et. al, usually involves a visualization or representation (e.g., a graph) that can be used to "highlight the most important aspects of what has been learned about the system in such a way that it can be understood by someone who does not know all the underlying details." This communication skill is especially important in fields involving complex and interrelated systems, such as those observed in physics and engineering. The ability to share useful information with colleagues without going through all of the underlying details and mechanisms is crucial. Accordingly, the two fundamental characteristics associated with this particular practice, as summarized in Tab. 5.8, are: i) a general process of communication (detailed in Tab. 5.8) and ii) the demonstration of an understanding that has been reached about the system.

For example, consider Excerpt 30 from Group E. At this stage, the group has begun to construct a Newtonian gravitational force model, but is struggling with its implementation. A brief interaction with the TA shows them communicating information about their understanding of the underlying concept of circular motion, as well as an understanding of the power and generalizability of the program. After this interaction, the group continues with the construction of the Newtonian gravitational force, and more specifically, its direction.

About halfway into the program, the group is struggling (line 231) to construct their Newtonian force model. The TA recognizes that they need a little help, and asks for them to explain their process (line 232):

SB: *(231)* Physics man... this is a mess [points to scratch work on WB].

TA: *(232)* No no, go ahead and explain...

SB: *(233)* Okay, so...

SB: *(234)* With that beautiful little formula right here [points to Newtonian force equation]...

SB: *(235)* We decided... this force has to be negative.

SB: *(236)* Because our initial momentum is five thousand in the positive y-direction.

TA: *(237)* Okay, I can dig that.

SB: *(238)* And then our unit vector {for position} right now, is one zero zero [inaudible].

SB: *(239)* So if we have the force multiplied by that, negative, so it has to be negative.

SB: *(240)* Then this {the momentum/velocity} will slowly start approaching negative five thousand here in the x-direction.

SB: *(241)* And then once that reaches {negative} five thousand, then our position is here at zero one zero...

SB: *(242)* And then since it's {the force} negative, it'll move it downward.

SB: *(243)* And that will happen at every step [draws four points on a unit circle].

TA: *(244)* Okay good.

Thus, a member of the group can be seen communicating information (lines 234-243) about the way that the force, momentum, and position are related at various points on the x- and y-axes for a circular trajectory. Although just one member of the group is doing a majority of the communication, they are acting as a spokesperson or a representative for the group (line 235). This information shows a clear understanding of the rather complicated interrelation (i.e., sinusoidal and out-of-phase) of these physical quantities.

However, the TA continues to press them on their understanding (lines 245, 248, and 250) by asking them to consider positions other than those on the x- and y-axes:

TA: *(245)* What about here [draws a dot in the first quadrant]?

SD: *(246)* Point five...

SB: *(247)* Then it'll be... the square root of two, square root of two, zero.

TA: *(248)* Okay, what about here [draws a dot in the second quadrant]?

SB: *(249)* Square root of two, negative square root of two, zero.

TA: *(250)* What if it's not at forty five degrees?

TA: *(251)* What if it's just at some arbitrary angle?

SB: *(252)* Well, the reason that were doing this...

SD: *(253)* The r hat is gonna update as it goes.

TA: *(254)* Okay...

SD: *(255)* So you don't need to know that.

SB: *(256)* Yeah you don't need to know that...

TA: *(257)* Okay, that's fine.

In response, the group demonstrates a strong understanding of not just the interrelation between physical quantities (lines 234-243), but also of the computational power of their program. That is, another member of the group articulates (line 253) that their definition of the direction of the force in code (i.e., $\hat{r}$) will automatically update to account for these various/arbitrary positions.

To summarize, this excerpt shows a TA interaction focusing on the construction of the Newtonian gravitational force acting on the satellite. The group can be seen *communicating* information about the interrelation of the position, force, and momentum of the satellite. Through this dialogue, they are demonstrating a clear *understanding* of these interrelations, as well as a clear understanding of the power and generalizabilty of their program. Given this communication and demonstration of understanding, this excerpt can be classified as an illustration of the computational practice of communicating information.

Chapter 6

Discussion

This chapter provides a discussion of the reasons why we might observe certain practices, the limitations of the underlying framework, and the constraints of the course and activity.

6.1 Findings

In the sections that follow, we present our findings of the common, less common, and the unobserved practices within our data set. The common practices are those that were identified at least three times in a majority of the groups (individual practices occurred between zero and seven times per group, with an average of three occurrences). The less common practices are the remaining of the observed practices. The unobserved practices were not identified at all. Along with some of the statistics of the frequencies of these practices (i.e., raw numbers and percentages), we provide their definitions and reference detailed examples in the appendices. Additionally, and perhaps most importantly, we discuss the reasons as to why a particular practice might have a given frequency.

6.1.1 Common practices

Eleven of the practices laid out by the framework have been identified multiple times in eight of the groups that were analyzed. Accordingly, these practices (listed in Tab. 6.1) are deemed common and are discussed below and in App. A. It is important to pay attention to these practices because, as instructors, we not only want students to be able to accomplish tasks, but we also want to make sure that they are engaging in things like critical and computational thinking while doing so. Being able to identify and encourage these practices as they occur (or don't occur) in a classroom, therefore, is crucial to effective pedagogy and course design. Accordingly, we must develop clear and reliable definitions for each of the common practices.

Category	Practice	Number	% of category	% of all
Data	Creating data	27	31	9
	Analyzing data	23	27	8
	Visualizing data	36	42	13
Modeling	Designing models	32	33	11
	Constructing models	18	19	6
	Assessing models	27	28	9
Problem solving	Creating abstractions	22	27	8
	Programming	21	26	7
	Troubleshooting and debugging	24	29	8
Systems	Thinking in levels	18	33	6
	Communicating information	23	43	8

Table 6.1: The computational practices that have been deemed common are shown with the number of times each practice was identified, the percentage of its category that it occupies (i.e., the number of times a practice was observed divided by the total number of practices from that category), and the percentage of all the practices that it occupies (i.e., the number of times a practice was observed divided by the total number of practices from all categories). Horizontal dividers separate the different categories (i.e., data, modeling, problem solving, and systems thinking).

Overall, there are a number of reasons that we have commonly observed these practices in terms of the learning goals and the course design. The learning goal of being able to use mathematical and computational thinking (P4) comes into play any time students are dealing with the abstractions that they have defined in the calculation loop, which are needed to be able to accurately predict motion using the Euler-Cromer algorithms. The learning goal of being able to analyze and interpret data (P3) shows up anytime students print or visualize the data representing a physical quantity, a common troubleshooting technique and something required by the problem statement. The learning goal of being able to develop and use models (P1) shows up whenever students are working to construct the various force models covered in the course, which are necessary for an accurate trajectory of the satellite. The learning goal of being able to obtain, evaluate, and communicate information (P7) shows up continually as groups are engaging in discussion with each other and with the tutors, something that we strongly encourage through tutor questions. All of these learning goals seem to strongly influence the practices that we observe.

For example, the practice of **visualizing data** involves the *production* of a visualization that clearly *conveys* some information. The computational production of a dynamically updating graph of the distance between the satellite and the Earth vs. simulated time can be produced and used to clearly convey information about the nature of the orbit (i.e., how close the orbit is to perfectly circular). This type of practice was observed 36 times across the data set, accounting for 42% of the data practices, and 13% of all practices.

Visualizing data is expected to show up commonly in our data given the learning goal of analyzing and interpreting data (P3). One of the ways that data can be analyzed and interpreted is with a visualization. Specifically, the visualizations we see students making are that of the trajectory, the force, the momentum, and the graph of distance vs. time. These visualizations efficiently convey information both to the students and to the TA (e.g., the visualization of the force conveys information about its central nature).

Additionally, students have been working with MWPs to produce dynamic visualizations of motion since the first week of class. The first and second computational problems, focusing on boats and hovercrafts, respectively, were visualized in a number of ways (e.g., producing visualizations of their trajectories). In other words, students are familiar with the visualization of data coming into the third problem. Not to mention, the problem statement, shown in Fig. 3.3, explicitly asks students to produce a simulation/visualization of an elliptical orbit.

Furthermore, after a group has correctly constructed the Newtonian gravitational force, many of the tutor interactions focus on the generation of a graph to clearly show that the satellite isn't traveling in a perfectly circular orbit. For example, consider Excerpt 38 from Group A where the TA is prompting the group to add in a graph to their code:

TA: I'd like you to graph the orbital... the magnitude of the radius of the orbit vs. a function of time...

SC: Okay...

TA: And have that graphed as well and it updates

SC: Okay.

The tutor is presenting the additional goal of producing a graph to the group. After this interaction, the group adds a graph to their program and using the results to conclude that the satellite is not traveling in a perfectly circular orbit. This graph can be used to efficiently convey information about how close the satellite is to perfectly geostationary.

Among all things, we want P^3 students to understand that computers can be used to quickly generate visualizations that can easily be tweaked, and that those visualizations can be useful when it comes to understanding and communicating the physics of the realistic phenomenon being modeled. Accordingly, we are likely to commonly observe this and other (see App. A) practices in our data.

6.1.2 Less common practices

Five of the practices laid out by the framework have been identified relatively fewer times and in only five of the groups that we analyzed. Accordingly, these practices (listed in Tab. 6.2) are deemed less common and are given a reasonable amount of attention here and in App. B. The data practices were either unobserved or commonly observed, and so this table shows only the less commonly observed modeling, problem solving, and systems practices.

Category	Practice	Number	% of category	% of all
Modeling	Understanding concepts	7	7	2
	Finding and testing solutions	13	13	4
Problem Solving	Assessing solutions	9	11	3
Systems thinking	Investigating systems	13	13	4
	Understanding relationships	13	13	4

Table 6.2: The computational practices that have been deemed less common are shown with the number of times each practice was identified, the percentage of its category that it occupies, and the percentage of all the practices that it occupies.

Overall, there are a number of reasons that we observed these practices given the learning goals, the design of the course, and the actual problem students are solving. The learning goal of being able to engage in argument from evidence (P6) manifests when students are defending the use of a particular model, which is necessary to choosing the most appropriate force model (i.e., the Newtonian gravitational force). The learning goal of being able to construct explanations (P5) happens when students are comparing different force models, which similarly is needed to choose the most appropriate force model. The learning goal of being able to obtain, evaluate, and communicate information (P7) shows up continually as groups are engaging in discussion with each other and with the tutors, something that we strongly encourage through tutor questions. The learning goal of being able to plan and carry out investigations (P2) happens frequently as groups are dealing with the complicated system that we have provided to them, which is a crucial part of programming and computer engineering. The learning goal of being able to develop and use models (P1) shows up whenever students are working to construct the various force models covered in the course, which must be correctly translated into code for the program to run correctly. However, one of the reasons as to why we only observe these practices less commonly relative to the other practices – aside from the limitations of the framework and the course design – may be due to the variation in student preparation coming into the course.

For example, the practice of **assessing solutions** involves the *comparison* of two or more different solutions. This is different than just testing solutions, given that it focuses on a comparison between two or more solutions. Groups often compare the expected behavior using a local gravitational force to using a Newtonian gravitational force. In this way, multiple solutions are assessed in terms of their validity. This type of practice was observed 9 times across the data accounting for 11% of the systems thinking practices, and 3% of all practices.

We expect to see this practice in our data given the learning goal of being able to construct explanations (P5). That is, we not only wanted students to make comparisons between models, but we also wanted them to clearly explain those differences. These long and often complicated explanations, then, are often a clear indication of a group assessing a solution.

Additionally, many of the tutor interactions can encourage this practice. For example, consider Excerpt 22 from Group B where the TA is asking them about the two models they have written on their board:

TA: So these two forces that you have on your board...

TA: Fg and Fcent...

TA: Which of those do you want to use?

SB: We are thinking Fcent...

TA: Why?

SB: Because we have everything we need for it...

Here the models that the group is comparing are the gravitational force and the centripetal force. Specifically, the group explains the difference between the two as being in terms of the requirements of the model. After this interaction, the group runs through the individual elements of the model that they have decided on, and begin to construct it in code. Given interactions like these, we frequently observe this type of practice in our data.

However, one reason that we observe assessing solutions less commonly within our data might be that some groups are better or worse at making comparisons – a key characteristic of this practice. Most groups take a guess and check approach rather than a contrast and compare approach [50], and so we only see this practices less commonly relative to the rest. For example, Excerpt 7 from Group G shows a common exchange:

SC: But I feel like we should just try this one Fcent equation...

SC: And see if it works

SC: Because if it doesn't, then we can worry about it later

SB: Yeah okay, lets just do that.

Here, the group tentatively decides on a model without comparing it to any other possible models (e.g., a Newtonian gravitational force). A group with at least one member that is highly motived to compare the pros and cons of different solutions will likely engage in this and other (see App. B) practices more often.

6.1.3 Unobserved practices

Six of the practices laid out by the framework have not been observed at all. Accordingly, these practices (i.e., collecting data, manipulating data, choosing computational tools, developing modular solutions, preparing problems, defining systems) are given their due attention here and in the appendices. Although these practices are unobserved, it is still important to discuss why they are unobserved.

There are a number of reasons that we did not observe these practices. Specifically, there is a lack of learning goals related to data collection, data manipulation, choosing tools, developing modular solutions, preparing problems for solutions, and defining systems and managing complexity. Further, given the lack of focus on these learning goals, many tutor interactions worked to intentionally dissuade students from engaging in these unobserved practices.

For example, the practice of **collecting data** is not expected to show up in our data given that there are no sensors or meters that are provided to students, as they might be in a lab setting. The only tool students are required to use is the computer along with VPython. This tool, although it can be used to handle the collection of data, is primarily meant to be used to create the data algorithmically. This aligns with the learning goals of developing and using models (P1) to create data, rather than collecting it. Given the lack of these types of learning goals, we do not expect students to engage in this and other (see App. C) practices.

6.2 Limitations

Although the framework gives a solid foundation and a good starting place, it does not come without its limitations that influence the practices we were able to identify. Additionally, the course and its design invariably constrains the practices that we have and have not observed. Furthermore, the activity itself places additional constraints on the practices available to the students. Finally, the qualitative lens that we have used influences the analysis we have conducted. In this section, we describe the limitations of the framework, the constraints of the course and activity, and the primary lens we have used to guide our analysis. Finally, we discuss how those limitations relate to the practices we have been able to confidently identify. It is important to note that for every limitation, we also saw possible research opportunities, which are described in Ch. 7.

It is also important to recognize that our analysis has focused on one specific problem (i.e., the Newtonian gravitational force problem detailed in Sec. 3.3) in the early stages of the development of P^3. Even though our scope of analysis is fairly restricted, our research is still useful in adding "second-order terms" to the broad definitions presented by Weintrop et. al, as well as to future research on the computational practices within physics. Expanding our analysis to other problems (e.g, spring forces) in future iterations of P^3 or to other implementations of the classroom (e.g., the electricity and magnetism version, aptly named EMP^3) will invariably introduce new or otherwise previously unobserved practices. In addition, MSU's new Studio Physics courses are specifically designed to engage students with collecting and analyzing data.

6.2.1 Framework

Although the framework that we used has many benefits, there are also some limitations that come along with it. For the most part, these limitations are centered on the broad definitions that are provided by Weintrop et. al. Although their broad definitions are widely applicable to many different types of science and mathematics classrooms generally, they can be rather vague/ambiguous when applying them to a particular classroom. Accordingly, the following sections describe the vague/ambiguous definitions within P^3 in terms of the four different categories of practices: the data, modeling, problem solving, and systems thinking practices.

Additionally, the framework itself has a rather narrow focus (i.e., on practices indicative of computational thinking), which could be expanded to capture practices that are indicative of other types of thinking or cognitive development. For example, P^3 does an excellent job of facilitating the development of physics identity within its students – something the framework is not intended to capture. Despite these limitations, the framework does capture many practices well (see Sec. 5.2).

6.2.1.1 Data

Within the data practices, it is often difficult to identify precisely when students are *advancing* toward the goals of the problem through the creation of data. Although the construction of the computational algorithm that creates the data can be easily identified in code, the advancement that they undergo is more subjective. The goals of the problem (e.g., simulating an orbit or producing a graph) often take the entire two hours of the class to be accomplished, and the different paths to get there are winding and often non-linear. For example, after constructing a working force model in code, a group is ready to automatically and algorithmically create a set of data representing the force on the satellite. However, this possibly incorrect/inaccurate set of data does not immediately or completely advance them toward their goal of creating an elliptical orbit. Still, this incorrect set of data can eventually prompt them to correctly modify their force model – ultimately advancing them toward their goal of creating an elliptical orbit. In other words, sometimes you need to take a step back before you can take two steps forward. Given this difficulty in defining what constitutes advancing toward a goal, identifying this practice was often difficult.

6.2.1.2 Modeling

Within the modeling and simulation practices, it is often difficult to identify when a group is *progressing* in their understanding of a concept as they interact with the models of the course. Although it is easy to identify the different force models, and to identify when a group is interacting with them (e.g., designing on the whiteboard or constructing in code), it is more difficult to say when a group is using that model to make progress in their understanding of the underlying concepts. Not to mention, it is difficult to clearly define what it means to truly *understand* something. For example, groups are frequently seen interacting with the computational model of the Newtonian gravitational force. As they necessarily construct the direction of the force in terms of the separation vector and its magnitude, they should be using it to develop an understanding of the way that the force changes direction over time. This understanding, although difficult to directly observe, can be teased out through tutor interactions (see Sec. 5.8). It often takes a long line of tutor questioning to confidently check a group's understanding. Given this difficulty in defining what constitutes progressing in the understanding of a concept, identifying this practice was difficult.

6.2.1.3 Problem solving

Within the problem solving practices, it can be difficult to clearly define what it means for a group to be *systematic* while troubleshooting and debugging their code. Although it is relatively easy to identify when a group has isolated and corrected an error, it is not so easy to identify when a group is being systematic in that process. Although many groups devise plans to methodically isolate and correct errors until they have successfully troubleshooted or debugged their code (see Ch. 4), those plans are not always successful. Additionally, many groups stumble haphazardly on unexpected errors, and correct them in a similar fashion. Given this difficulty in defining what it means to systematically troubleshoot and debug, identifying this practice was difficult.

6.2.1.4 Systems

Within the systems thinking practices, understanding relationships in a system is ambiguously defined – it can have a significant amount of overlap with the practice of designing a computational model (see Sec. 5.2.3). This overlap ultimately depends on the ambiguous definition of a system given by Weintrop et. al. For example, if a computational force model can be considered a system, then anytime students are designing a computational model they are also understanding the relationships in a system. Rather, if a system refers to something more like a collection of files that are related to one other to create a program (e.g., a Python script that loads different modules/libraries), then understanding the relationships in a system would most likely not occur alongside designing a computational model. This type of ambiguity has a tendency to lower confidence during inter-rater reliability. Accordingly, this practice is confidently observed less often.

6.2.2 Course

Although the course that we collected our data from was well designed and implemented (see Ch. 3), it was not conducive to some of the practices laid out by the framework, stemming from the many design choices that were made early on. These crucial design choices and their ramifications on our analysis/findings are described in the sections that follow.

6.2.2.1 Group vs. individual

Given that the course followed a group-based approach, it was often difficult to say which individual students were actively engaging in the practice. For example, the process of agreeing on the assumptions of the force model often involves multiple viewpoints that must be taken into account simultaneously. Accordingly, it is difficult to ascribe the practice to any individual from the group. Additionally, just because individuals are not physical engaged (e.g., talking or writing) does not mean that they are not mentally engaged. However, follow-up interview data could be used as additional evidence for ascribing a particular practice to a specific individual.

6.2.2.2 Scaffolding vs. discovery

At the beginning of the course, a "norming" day was held as a means to provide students with an overview of the course structure and a reason as to why it was being run that way. An important component of that day was on the modeling component of the course, illustrated in Fig. 6.1. Given this focus on modeling at the beginning of the course, it is no surprise that we frequently observed students engaging in the various computational modeling practices defined by Weintrop et. al.

Additionally, the course was reasonably scaffolded with the pre-class reading and pre-

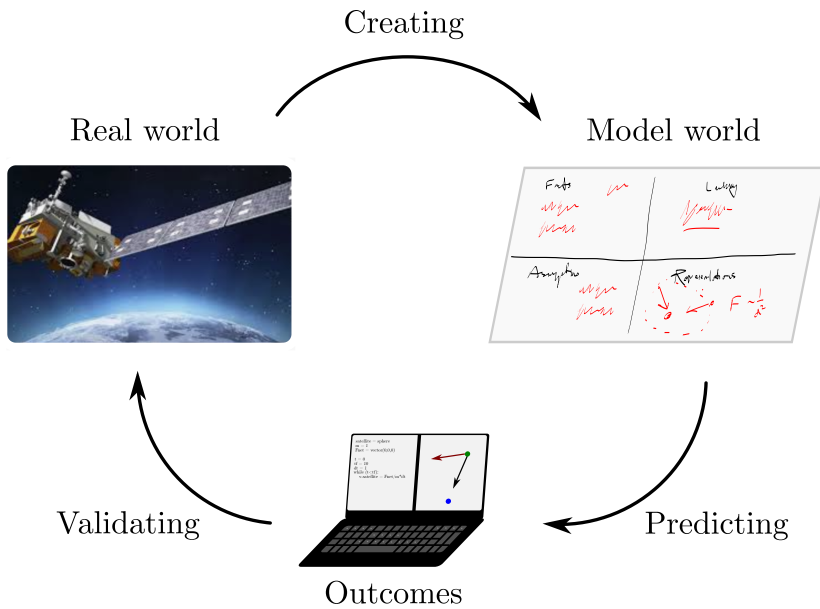


Figure 6.1: The iterative process of modeling physical systems that was described to the class on the first day.

class homework. The pre-class reading is meant to introduce the fundamental concepts while the pre-class homework is meant to check for correct application of those concepts. This preparation helps the students to frame the problem in a way that uses many of the practices. For example, some of the homework problems (see Sec. 3.7) focus on VPython errors that must be identified. Given this type of preparation, many students engaged in the practice of things like troubleshooting and debugging and programming.

Moreover, the frequent tutor interactions throughout the course are meant to check for understanding of the concepts and their application while in class. However, these frequent tutor interactions make it difficult to say whether or not the practices observed are generated by the students or by the tutors – a "social observer" effect. Many times, TAs dissuade students from engaging in certain practices, and intentionally encourage them to engage in others. For example, any group that gets lost in the PhysUtil system file will invariably be encouraged to stop that and start focusing on the MWP.

6.2.2.3 Intro vs. advanced

The course was designed around introductory physics concepts, which limited the types of forces and motion models that could be analyzed. The analysis of a more advanced classroom (e.g., computational Newtonian mechanics using higher order algorithms) may provide additional practices. For example, in more advanced physics classrooms we may expect groups to *optimize* their models by adding more than just one force – something that is lacking in the Weintrop framework. In other words, we can begin to search for new and unique practices in a more advanced P^3-style classroom.

An important limitation of the study is that we did not focus on classifying the levels of sophistication of the practices. Rather, we just focused on identifying them. As computation continues to grow in industry and academia [3], and as new and more advanced computational techniques are discovered, it is important that we begin to classify the Weintrop practices in terms of their levels of sophistication. Although we do not expect to see extremely unique or sophisticated practices in our data, it is something that should be focused on in future research.

6.2.3 Activity

At the level of the activity itself, its boundaries limit the practices that we observe. For example, the problem statement contains many direct tasks, as well as a few that are implied. Additionally, the focus of the activity is on relatively intuitive physical concepts (i.e., the gravitational force and Newton's second law). These types of requirements and their implications on our findings are described in the sections that follow.

Given that the problem statement contains both explicit and implied tasks, it has a large influence on the practices that we do and do not observe. Specifically, the direct tasks in the problem statement are to i) produce a simulation of an elliptical orbit, ii) produce a diagram showing the momentum of the satellite, and iii) produce a graph of the radius of the orbit over time. Given the direct task of (i), we expect to see groups designing, constructing, and assessing models in code as they work to produce their physically accurate simulation (see Sec. 5.3). Additionally, given (ii) we expect to see groups analyzing and visualize data as they communicate information about the way that the momentum of the satellite changes over time (see Sec. 5.2). Similarly, given (iii) we expect to see students engaging in the practice of visualizing data as they communicate information about the radius of the orbit over time (see Sec. 5.8). The direct tasks lead to the more commonly observed practices.

The direct tasks in the problem statement are explicitly laid out for groups and so take precedence, whereas the implied tasks in the problem statement are often a difficult thing for students to infer on their own. For example, one implied task is to develop a proficiency in dealing with relatively small programming systems (i.e., the self-contained MWP). Another implied task is to develop an understanding of the concept of a directional unit vector as it shows up in the Newtonian force (see Sec. 5.2.8). These rather subtle implied task may be reasons that we observe groups engaging in some of the practices less commonly (see Sec. 6.2).

6.2.4 Analysis

It is important to note that this study was conducted through the lens of an instructor, looking to effectively increase the amount of computation taught at the introductory physics level. Accordingly, there was a heavy focus on the way that the tutors interacted with the students to either encourage or discourage certain practices. Although these types of student-instructor interactions are unavoidable in most classrooms – especially in P^3 type classrooms – our focus on them may have made it more difficult to identify the practices coming solely from student-student interactions.

Additionally, given the heavy focus on computation and computational thinking in our analysis (see Ch. 2), other important types of thinking (e.g., creative thinking) may have been overlooked. A detailed analysis of the related analytic problem (see Tab. 3.1), which does not have a computational element, may provide additional insight into the practices indicative of creative and other types of thinking.

Furthermore, the type of data that we had to work with (i.e., in-class video of group work) often made it difficult to ascertain exactly what students were thinking as they worked, and may have influenced the practices that we observed. Conducting post-class might have helped to validate researcher inferences – something that should be looked into in future research.

Chapter 7

Conclusion

7.1 Summary

This thesis attempts to more clearly and precisely define the computational practices observed within introductory computational mechanics that are indicative of computational thinking. Although a set of preliminary practices – defined in a framework developed by Weintrop et. al – provide a starting point (see Sec. 2.1), they were sufficiently vague and/or ambiguous as to warrant further definition. This is especially true within the discipline of introductory physics. Accordingly, this thesis i) describes the overall process of defining the computational practices common to introductory physics that are indicative of computational thinking and ii) presents those definitions with concrete examples (see Chs. 5 and 6 and Apps. A–C).

We began by collecting data from a classroom that was designed according to multiple learning goals and theories of learning. Specifically, a problem-based learning environment, called Projects and Practices in Physics, focusing on the principles of constructive alignment and using the theoretical framework of communities of practice [47]. This type of classroom was a rich environment to conduct qualitative education research within, and so we collected multiple streams of data (see Sec. 3) for possible analysis [51, 52]. Although this classroom was an ideal place to search for instances of groups engaging in computational practices –

helping us to more clearly and precisely define them – it is important not to generalize our findings to classrooms that are sufficiently different.

Early research in computational physics education suggested continuing to investigate a phenomenon called "physics debugging [31]." Accordingly, a pilot study was conducted in the Fall of 2016 to better understand this phenomenon – which ultimately raised more questions than it answered (see Ch. 4). These additional questions motivated the need for a more rigorous and in-depth analysis of the data so that we could make and support stronger claims.

Our corpus of data, consisting of in-class video of nine groups working on three different computational physics problems, was transcribed verbatim with gestures and actions indicated. Similarly, overhead video and computer screencasts were collected to cross-reference with the transcripts. Given these three streams of data, we performed both a task and a thematic analysis (see Secs. 2.4 and 2.5) to help facilitate a more rigorous and in-depth analysis so as to generate clear and precise definitions of the common computational practices that were observed.

The common practices that we observed were: creating, analyzing, and visualizing data in the data practices; designing, constructing, and assessing models in the modeling practices; creating abstractions, programming, and troubleshooting and debugging in the problem solving practices; and thinking in levels and communicating information in the systems thinking practices. The less common practices that we observed were: understanding concepts and finding and testing solutions in the modeling practices; assessing solutions in the problem solving practices; and investigating systems and understanding relationships in the systems thinking practices. The unobserved practices were: collecting and manipulating data in the data practices; choosing computational tools, developing modular solutions, and preparing problems for solutions in the problem solving practices; and defining systems in the systems thinking practices. Along with these definitions (see Secs. 5.2 and 6.1, and Apps. A–C), we provide a detailed account of the data reduction, coding process, and inter-rater reliability (see Sec. 5.1).

7.2 Future research

Although we have attempted to precise some of the broad definitions of the computational practices that are indicative of computational thinking as provided by Weintrop et. al, more research is needed to fully understand them within and beyond the discipline of introductory physics. The findings of this thesis, though useful, have raised additional questions and present many opportunities for future research.

To start, a deeper analysis of the Newtonian gravitational force problem as presented in P^3, and focused on in this thesis, could be pursued. Additional types of data (e.g., post-class interviews) could be collected to provide more information on the way students perceive and experience the different practices that they are engaging in.

Additionally, a broader analysis of all of the mechanics problems presented in P^3 could be conducted. Although we have focused our analysis on one particular problem near the beginning of the course, there are other computational problems focusing on other mechanical concepts (e.g., collisions or rotation) occurring later in the course that my provide additional insight into the associated practices. It may also be of interest to investigate the way that these practices evolve over time as the course progresses.

Further, our analysis can be extended beyond an introductory mechanics course (e.g., advanced mechanics or introductory electricity and magnetism). There are many other physical concepts that can be, and sometimes must be, used while solving engineering problems (e.g., Lagrangian mechanics or cyclotron motion). Similarly, the Euler-Cromer algorithm highlighted in this thesis is not the only one, and is not always the most precise. More advanced classes focusing on more complicated yet more precise algorithms might be of future research interest.

Although P^3 was well suited to the analysis that we conducted, not all classrooms subscribe to its format. Accordingly, extending this type of research to other physics classrooms, that at least utilize computers in some capacity, would be of value.

7.3 Concluding remarks

A better understanding of modern scientific practices can only help to inform the many decisions that must be made while designing a course so as to foster the learning of knowledge, skills, and computational thinking. As student-centered learning environments like P^3 become increasingly popular, and as computation continues to permeate the STEM disciplines, our findings contribute to that understanding and present many opportunities for continuing research.

APPENDICES

Appendix A

Common practices

The following sections describe the common practices that we observed.

Creating data

The practice of **creating data** involves the construction of an *automatic* or algorithmic process that will quickly produce a large set of data and using that set of data to *advance* toward their goals. For example, constructing an Euler-Cromer algorithm to create a set of data representing the position of the satellite over time advances the group toward their goal of simulating the orbit of the satellite (see Sec. 5.2.1). This type of practice was observed 27 times across the data set, accounting for 31% of the data practices, and 9% of all practices.

Creating data is expected to show up commonly in our data given the learning goal of using mathematical and computational thinking (P4). We wanted students to take advantage of the Euler-Cromer algorithms to generate the sets of data representing the position and momentum of the satellite over time. We also wanted them to construct and use different models to generate the set of data representing the force over time. These algorithms and models of motion require a lot of mathematical and computational thinking, aligning well with that learning goal.

Additionally, the problem cannot be solved analytically with just introductory level mathematics. However, it can be solved numerically with introductory level mathematics and computation. For example, consider Excerpt 7 from Group C where the TA is prompting the group to create data:

TA: But you need the force to keep changing direction as it moves around

SC: Right

TA: So you can't just hard code the numerical value that you found last time

SC: Oh... because this position of the satellite is going to change, which means the force is going to change...

TA: Exactly

SB: Oh, gotcha

Here, the tutor is facilitating the creation of data by focusing on the way that the force needs to continually change as the satellite moves. After this interaction, the group goes on to code their net force as a position-dependent function rather than a hard coded value. These types of interactions usually initiate the process of designing, constructing, and assessing computational models and algorithms that ultimately create large sets of data.

Overall, we want students in P^3 to be able to use simple control structures with force models of varying complexity to generate large sets of data for complicated and realistic motion problems – to create data.

Analyzing data

The practice of **analyzing data** involves a broad process of analysis that includes sorting data into *categories*, looking for *trends*, looking for *correlations*, and/or identifying *outliers* that can be used to reach some *conclusion*. For example, when a print statement is used to verify that the force acting on the satellite has the trend of remaining constant in simulated time, a conclusion can be drawn about the correctness of the underlying force model (see Sec. 5.2.2). This type of practice was observed 23 times across the data set, accounting for 27% of the data practices, and 8% of all practices.

Analyzing data is expected to show up commonly in our data given the learning goal of analyzing and interpreting data (P3). We recognize that large sets of data need to be generated using computational algorithms and models, and that these sets need to be analyzed in order to asses and validate the underlying algorithms and models. There are many different ways to analyze data, but it usually leads to some interpretation or conclusion that is made. Given the utility of analyzing data when it comes to designing, assessing, and constructing the underlying computational models, we expect to see this practice commonly in our data.

One technique of analysis that is often suggested is to use a print statement in the calculation loop so the data itself can be analyzed. For example, consider Excerpt 23 from Group I where the TA makes this type of suggestion:

TA: Check like, so I know you know how to do this... use a print statement.

TA: Check if it's doing anything, make sense of where it's not, or if it's running or if it's not running...

SB: Yeah, okay.

TA: Talk everybody through what you're doing though...

SB: Yeah, I will.

Here, the TA suggests that they use a print statement so that they can analyze the data representing the force acting on the satellite and to make decisions based on that analysis. After this interaction, the group constructs a print statement in their calculation loop to print the continually updating net force acting on the satellite, thereby creating a set of data. They then analyze this set as they assess the underlying force model. These types of TA interactions focusing on print statements usually initiate the practice of analysis of a set of data.

Ultimately, we want students in P^3 to be able to interpret and attach meaning to the patterns that can be found in large sets of data.

Designing computational models

The practice of **designing computational models** involves *defining* the individual components of a model, *relating* the model to the physical phenomenon under investigation, and articulating what *predictions* the model will be able to make. For example, the mass of the satellite, the magnitude of its velocity, the radius of its orbit, and the polar angle that it makes can all be separately defined in code. Additionally, these individual components can be combined, following an equation, to produce the expected oscillatory motion of the satellite. Finally, the resulting force model can be used to make predictions about the motion of the satellite (see Sec. 5.2.3). This type of practice was observed 32 times across the data set, accounting for 11% of the data practices, and 33% of all practices.

We expect to see this practice commonly in our data given the learning goal of developing and using models (P1). The course was specifically designed to focus on different force models with a range of complexities. That is, the first three weeks of the course focuses on a constant zero force, a constant non-zero force, and a non-constant force model. Given that the students must actually develop these models in code, we frequently observe them designing computational models.

Further, the four-quadrants are meant to scaffold the design process by highlighting the knowns, unknowns, and assumptions of the model (see Ch. 3). This scaffolding often facilitates the design process by helping groups to define the individual elements of their model. For example, consider Excerpt 12 from Group F where one student is clear to articulate the individual elements they are defining by writing them on the four-quadrants:

SA: So I'm just gonna go ahead and define those over there then.

SA: [writing on 4Q].

SA: Should we do that?.

SB: Yeah go ahead and... We have the mass.

SB: And the position of the satellite.

SC: And the velocity from last time.

SA: Okay hold on [writing them down].

Here, the individual elements of the mass, position, and velocity of the satellite are individually defined. Once this is done, they begin to relate them to one another and to construct their centripetal force model. That is, we see students using the four-quadrants to help them design their model.

Mainly, we want students in P^3 to be able to define the individual elements of a model, relate them to each other, and make predictions using various computational force models.

Constructing computational models

The practice of **constructing computational models** involves *implementing* new behavior in code by either *creating* a new model or by *extending* a previously written model. For example, implementing an attraction between two massive objects in code can be achieved through the construction of a force model. This behavior can be implemented in one shot (e.g., immediately constructing a Newtonian gravitational force that can handle elliptical orbits) or can be implemented by successively extending an approximate model (e.g., moving from a constant gravitational force that generates a parabolic trajectory, to a centripetal force that generates a circular orbit, to a Newtonian gravitational force that generates an elliptical orbit). This type of practice was observed 18 times across the data set, accounting for 19% of the data practices, and 6% of all practices.

Constructing computational models is expected to show up frequently within our data given the learning goal of developing and using models (P1). Developing a model in code invariably requires students to map mathematical equations onto VPython syntax. This involves using proper operations (e.g., adding, multiplying, calculating magnitudes), using proper order of operations (e.g., using parentheses to clear up any ambiguity), and ensuring computational abstractions are of the proper type (e.g., that position is a vector, or that distance is a scalar). Given that these things must all be constructed in code, we frequently observe students constructing models.

Additionally, many tutor interactions are intended to facilitate this practice. For example, consider Excerpt 9 from Group I where the group has designed their model and is beginning to construct it in code:

TA: No, what you have their on the whiteboard looks good...

SD: Okay so we just need to like take this equation and like...

SD: Put it in the program...

TA: Right...

SD: Right, but how do we do that?

SC: So just take big G... And then like multiplied times...

SC: m sat, err, yeah the mass of the satellite.

SA: Okay... [begins to type].

Here, the model they have designed is the Newtonian gravitational force and they begin to construct it in code in terms of the universal gravitational constant, the mass of the satellite and the Earth, and the satellite's position relative to the Earth. Given these types of interactions, we frequently observe students constructing models.

Ultimately, we want students in P^3 to be able to construct models in code, whether or not the models are correct.

Assessing computational models

The practice of **assessing computational models** involves identifying the *assumptions* built into a model and *validating* them by comparing to reality to ensure predictive accuracy. For example, groups frequently assume that the orbit of the satellite will be perfect circular. Although this assumption is a good starting point, it is invariably checked for validity when considering arbitrary initial conditions that lead to more general elliptical orbits (see Sec. 5.2.4). This type of practice was observed 27 times across the data set, accounting for 28% of the data practices, and 9% of all practices.

Assessing computational models is expected to show up frequently within our data given given the learning of developing and using models (P1). Once a model has been designed and constructed to a reasonable degree, it can be used to generate information (e.g., a trajectory of the satellite). This information can ultimately be used as evidence to make an argument for or against the validity of that model. Thus, throughout the process of designing, constructing, and most importantly assessing a computational model, students should be engaging in argument based on evidence.

Many tutor interactions can help to facilitate this practice as well. For example, consider Excerpt 15 from Group C where they articulate an assumption built into a model and validate its use given prompting:

TA: Yeah but when is that equation good?

SB: When its in free...

SC: Like when its falling...

TA: Right, close to the Earth.

SB: Yeah.

SC: Which is why we have that written here under assumptions {on the 4Q}.

TA: Okay good but... is that what you have over here?

SB: No.

SC: No we need a different equation...

Here, the poor assumption is that of a uniform gravitational acceleration, which invalidates their model. After this interaction, they scrap the local gravitational force and begin to try a centripetal force model. Given these types of tutor interactions, we expect to frequently observe students assessing models.

Overall, we want students in P^3 to be able to validate different computational models by identifying their assumptions, whether or not they did the design and/or construction themselves.

Creating computational abstractions

The practice of **creating computational abstractions** involves taking a physical *concept* and *representing* that concept in code. For example, the physical concept of the unit vector giving a proper direction to the Newtonian gravitational force acting on the satellite can be most easily represented in code by combining the position of the satellite and its magnitude (see Sec. 5.2.5). This type of practice was observed 22 times across the data set, accounting for 27% of the data practices, and 8% of all practices.

Creating computational abstractions is expected to show up frequently within our data given the learning goal of being able to develop and use models (P1). All of the models used in the course (i.e., the various force and motion models) have some mathematical form that can be translated into VPython syntax. That is, in order to construct a computational model, you must first create the computational abstractions that it depends on. Given the focus on modeling in the course, we expect to commonly observes students creating abstractions.

Additionally, some of the tutor interactions that we have observed facilitate this practice well. For example, consider Excerpt 9 from Group F where the tutor questions them on the definitions that they have in their code:

TA: So I see that you have those things defined on your whiteboard...

TA: But where do you have those defined in the code?

SA: But thats what I'm saying, thats what were working on.

TA: Okay, so what are you thinking then?

SA: We have these things [points to board] defined...

SA: And we're gonna like input those values for those variables...

Here, the definitions that they have on the whiteboard are the mass of the satellite, its speed, and radius of circular orbit. This interaction ultimately prompts them to construct the corresponding computational abstractions in code, whether they hard code values or construct more complicated functions. Given these types of interactions, we expect to commonly observe this practice in our data.

Ultimately, we want students in P^3 to be able to make abstractions in code when dealing with various physical concepts.

Computer programming

The practice of **computer programming** involves *modifying* code while *arranging* that code in proper syntax. For example, while modifying the force model in the calculation loop, all lines must be arranged with the proper indentation. In other words, aside from the validity of the force model, the syntax must be in order for the computer to be able to interpret things correctly and to run without error. This type of practice was observed 21 times across the data set, accounting for 26% of the data practices, and 7% of all practices.

Computer programming is expected to be commonly observed in our data given the learning goal of using mathematical and computational thinking (P4). Groups are working with MWPs in VPython (see Sec. 3.4.2.1), which comes with its own unique syntax that must be adhered to strictly. Although the syntax in VPython is very intuitive (e.g., calculating the magnitude of a vector can be done by calling the `mag()` function), small and sometimes difficult to find syntax errors (e.g., a missing parenthesis) can lead to frustrating runtime errors. Given these difficulties, we expect to see students engaging frequently in this practice.

Additionally, this practice is heavily scaffolded through tutor interactions. Given that many students have little to no prior programming experience, tutors sometimes guide students in their programming. For example, consider Excerpt 30 from Group D where the group knows what to do, but is unsure of how to program it:

SB: TA, we need help.

TA: Okay I can try...

SB: We don't know how to like take the magnitude of this.

TA: Where?...

SB: Right here, in our force, equation for the force.

TA: Ahh okay, you need to put parentheses.

SB: Where here?

Here, the tutor is reminding the group that the proper syntax that must be adhered to requires parentheses. After this interaction, they modify their code, and continue to design, construct, and assess the associated force model. Given these types of interactions, we frequently observe groups to be engaging in the practice of computer programming.

Mainly, we want students in P^3 to have experience with programming and the difficulties associated with it.

Troubleshooting and debugging

The practice of **troubleshooting and debugging** involves *isolating* an unexpected error in the code, *correcting* that error in a long-term and generalizable manner, and doing so in a *systematic* fashion where applicable. For example, without defining the initial momentum of the satellite as a function in terms of its previously defined mass and initial velocity, changing the mass of the satellite won't correctly propagate through the program, leading to unexpected and undesirable results. Systematically isolating the causes of errors (e.g., not defining the momentum in a dynamic way) allows for it to not only be corrected, but to be corrected in a long-term and generalizable manner (see Sec. 5.2.6). This type of practice was observed 24 times across the data set, accounting for 29% of the data practices, and 8% of all practices.

Troubleshooting and debugging is expected to show up frequently within our data given the learning goal of being able to develop and use models (P1). During the process of developing and using a model, unexpected errors frequently occur and must be corrected. These unexpected errors can involve things like syntax errors or unexpected/unphysical behavior. In either case, students must identify those errors, and ultimately correct them in a systematic manner. Given this focus on developing and using models, we expect to see this practice commonly in our data.

Further, many tutors intentionally guide groups as they troubleshoot and debug. For example, consider Excerpt 22 from Group H where the tutor points out that their force model in code does not match their force model on the board:

TA: Oh, I see what it is...

SB: What?

TA: Okay so in the denominator of your force, you have the magnitude of the position of the satellite.

SB: Right...

TA: But what do you have on your board?

SB: Ohhh...

SC: We need it squared.

Here, the incorrect force model produces an extremely large force that rapidly accelerates the satellite to ludicrous speed. This small error, although syntactically correct, produces unphysical results. After this interaction, the group modifies their code so that it accurately reflects the equation. Given these types of tutor interactions, we expect to see this practice commonly in our data.

Overall, we want students in P^3 to be able to handle unexpected errors that arise while programming, whether they be syntactical or physical.

Thinking in levels

The practice of **thinking in levels** involves breaking the MWP into different *levels* and attributing those different levels with their characteristic *features*. For example, the program as a whole can broken down into the two different levels of the initial conditions and the calculation loop (see Sec. 5.2.7). Each level has its own defining features: the initial conditions level is where time-independent computational abstractions can be defined, whereas the calculation loop is where time-dependent computational abstractions must be defined. This type of practice was observed 18 times across the data accounting for 33% of the systems thinking practices, and 6% of all practices.

Thinking in levels is expected to show up frequently within our data given the learning goal of developing and using models (P1). The Newtonian gravitational force model and Euler-Cromer motion algorithms constitute a model of motion that must be developed in code and ultimately used for some purpose. While students are developing this model of motion, they must maintain the overall structure of the MWP written in VPython (see Fig. 3.4.2.1) – without proper structure and syntax, the program as a whole runs into fatal errors. This structure that must be maintained, is naturally broken down into several different levels: the objects, initial conditions, time set-up, and calculation loop. These levels are indicated in the MWP with comments (e.g., `#Calculation Loop`), and each level has its own unique features. Maintaining these features for each level is critical to a runnable program.

Additionally, students are introduced to the concept of iterative prediction of motion as an algorithmic change in different physical quantities over time. Specifically, $\vec{p}_{\text{new}} = \vec{p}_{\text{old}} + \vec{F}_{\text{net}}\,dt$, $\vec{r}_{\text{new}} = \vec{r}_{\text{old}} + \vec{v}\,dt$, and $t = t + dt$, as described in the course notes (see Sec. 3.1). These time-dependent physical quantities can be contrasted with time-independent (or approximately time-independent) physical quantities (e.g., the local acceleration due to gravity). Identifying the correct time-dependence of a physical quantities is necessary to ensuring proper placement of its definition – time-independent quantities can be placed in the initial conditions level, whereas time-dependent quantities must be placed in the calculation loop. For example, consider Excerpt 17 from Group E where they are discussing the placement of a line of code:

SA: Do we need F net to be calculated inside the loop?

SA: That is do we need to recalculate F net every time? is it changing?

SB: No.

SA: So we could just throw it outside of the loop.

Here, the students (incorrectly) articulate that the net force does not need to placed in the calculation loop because it does not need to update. That is, they identify the different levels of inside and outside the loop, and correctly attributed the feature that updating quantities must be placed inside the loop, whereas other can be placed outside.

Above all, we want students in P^3 to understand the difference between time-dependent and time-independent physical quantities, and to be able to properly define and place them in code. Accordingly, we observe this practice commonly in our data.

Communicating information

The practice of **communicating information** involves the broad process of *communication* that ranges from pure *dialogue* to self-contained *visualizations* that communicate some *understanding* that the group has achieved. For example, an understanding of the complicated but powerful computational interrelation between the force, position, and momentum of the satellite is frequently communicated verbally within and beyond groups (see Sec. 5.2.8). This type of practice was observed 23 times across the data accounting for 43% of the systems thinking practices, and 8% of all practices.

Communicating information is expected to show up frequently within our data given the learning goal of being able to obtain, evaluate, and communicate information (P7). Once information has been obtained and evaluated, it is crucial to ensure that each member of the group can communicate an understanding of it. Accordingly, students are required to continually explain their thought process throughout the day. Given this focus on encouraging explanation, we expect to frequently observe students communicating information in our data.

Further, many tutor interactions can help to facilitate this practice. For example, consider Excerpt 35 from Group E where the TA continues presses them on their understanding of the direction of the force by asking them to consider positions other than those on the x- and y-axes:

TA: What about here [draws a dot in the first quadrant]?

SD: Point five...

SB: Then it'll be... the square root of two, square root of two, zero.

TA: Okay, what about here [draws a dot in the second quadrant]?

SB: Square root of two, negative square root of two, zero.

TA: What if it's not at forty five degrees?

TA: What if it's just at some arbitrary angle?

SB: Well, the reason that were doing this...

SD: The r hat is gonna update as it goes.

TA: Okay...

SD: So you don't need to know that.

SB: Yeah you don't need to know that...

In response to the TA prompting, the group demonstrates a strong understanding that their definition of the direction of the force in code (i.e., $\hat{r}$) will automatically update to account for these various/arbitrary positions. Given these types of tutor interactions, we frequently observe this practice in our data.

Ultimately, we want students in P^3 to be able to clearly communicate their understanding of physical concepts, both through dialogue and by generating visual representations.

Appendix B

Less common practices

The following sections describe the less common practices that we observed.

Understanding concepts

The practice of **understanding concepts** involves *progressing* toward a deeper understanding of a concept by *interacting* with a computational model. For example, while designing, constructing, or assessing a Newtonian force model in code, students progress in their understanding of the abstract concept of a unit vector as providing purely a direction to a physical quantity. This type of practice was observed 7 times across the data accounting for 7% of the systems thinking practices, and 2% of all practices.

We expect to see this practice in our data given the learning goal of engaging in argument from evidence (P6). Specifically, individuals must be able to defend their understanding of various physical concepts while using their program as evidence. Each program produces a number of pieces of evidence (e.g., graphs, numerical values, visualizations, etc.) that can be used to support claims of understanding. Accordingly, we expect to see students engaging in this practice frequently.

Further, many tutor interactions help to facilitate the understanding of many concepts. For example, consider Excerpt 25 from Group C where the TA is asking them to illustrate a point they are trying to make with their program:

SA: The force has to point in the same direction as the momentum of the satellite...

TA: Yeah but why are you saying that?

TA: Can you use your program to sort of prove that to me?

SA: Yeah, so, if you look at the arrows on the satellite.

SA: They always like move toward the Earth.

SA: So we know that the force has to be pointing toward the Earth.

SA: So our direction has to be correct....

TA: Okay... okay that makes sense.

Here, a student clearly uses the visualization of the momentum of the satellite to demonstrate her understanding of the relationship between the force and the change in momentum. Given these types of interactions, we expect to see groups understanding concepts in our data.

However, one reason that we observe understanding concepts less commonly within our data might be that certain groups are more or less focused on truly understanding the underlying material – and frame the problem as such [53]. In other words, groups are often seen as taking on an answer-making mode rather than a sense-making mode [52]. A strong focus on the understanding of the underlying material is a relatively rare occurrence, and so we only see this practice less commonly relative to the rest. For example, Excerpt 13 from Group E shows a more typical exchange that does not have a strong focus on understanding:

SD: So can you just... why are we using that {GmM over r squared equation} now?

SD: Like why don't we have to use that {mg} one?

SB: Why can't we just use this {mg} one?

SC: Well this one [points to Newtonian force]... let's just try it and see what happens...

SD: Okay.

Here, the group does not focus on understanding why they are using the Newtonian gravitational force, rather they just guess to use it and eventually check it later. Given these types of typical exchanges, we expect to see understanding concepts less commonly relative to the other practices.

Finding and testing solutions

The practice of **finding and testing solutions** involves *justifying* the use of a particular solution. Often, the particular solutions that we see are the different force models covered in the course notes (e.g., local gravitational force). As students progress from incorrect or approximate force models (i.e., the local gravitational or centripetal) to the correct model (i.e., Newtonian gravitational force), we see them continually testing along the way. For example, a group might recognize that the local gravitational force model does not allow for the satellite to travel in a bound orbit, and move on to searching for a new model. This type of practice was observed 13 times across the data accounting for 13% of the systems thinking practices, and 4% of all practices.

We expect to see this practice in our data given the learning goal of obtaining, evaluating, and communicating information (P7). Most importantly, groups are required to evaluate information by using their program to make predictions and to evaluate it in terms of its predictive validity. If the model is not justified, a new model must be sought out, and the process of testing begins again. Given this focus on evaluating information when it comes to the justification of a solution, we expect to see this practice in our data.

Additionally, many tutor interactions can facilitate the testing process. For example, consider Excerpt 20 from Group A where they are using a local gravitational force model with a deceptive satellite trajectory:

TA: So the problem is...

TA: If you look at your force, you have a local gravitational force...

TA: But that is only good when?

SB: When it's close to Earth.

TA: And is that what we have here?

SA: But it looks like its orbiting [points to screen]

TA: Its actually parabolic, I know it looks like its gonna orbit but its not

SB: Oh cause the force here is only in the x direction

TA: Right... so you need to change that...

Here, the tutor is prompting them to justify their force model by scrutinizing the resulting trajectory. After this interaction, they being to look for another type of force to construct in code – one that is capable of producing a closed orbit. Given these types of interactions, we expect to see this practice in our data.

However, one reason that we observe finding and testing solutions less commonly within our data might be that individuals vary in their desire to justify their actions – an important characteristic of this practice. This type of self-justification (i.e., being coherent and logically consistent) is rather difficult [54, 55], and so we only see this practices less commonly relative to the rest. For example, Excerpt 25 from Group D shows one such relatively rare instance of a group member clearly and correctly justifying her actions:

SD: No, but we have to put it down here [points to calculation loop].

SA: Why not just with all the other stuff up here?

SD: Because... Because it has to be able to change...

SD: If it has to change it has to go down here in the calculation loop...

Here, Student D justifies defining their force model inside the calculation loop given that it needs to change over time. Given that this exchange is atypical, we expect to see finding and testing solutions less commonly relative to the other practices.

Investigating systems

The practice of **investigating systems** involves *questioning* and *interpreting* data gathered from a system as a whole. For example, a graph of the set of data representing the distance between the Earth and the satellite can be questioned about its qualitative time-dependence (e.g., if it is constant, linear, quadratic, sinusoidal, etc.). This type of practice was observed 13 times across the data, accounting for 13% of the systems thinking practices, and 4% of all practices.

Investigating systems as a whole is expected to show up in our data given the learning goal of planning and carrying out investigations (P2). The act of planning is scaffolded by the four-quadrants – students must list their knowns, unknowns, assumptions, and draw out any representations. These quadrants help students to generate questions (e.g., "what are we even trying to figure out?") that can be investigated for answers. Given the focus on questioning in Weintrop et. al's definition of investigating systems as a whole, we expect to see this practice in our data.

Additionally, investigating systems as a whole likely shows up in our data given the learning goal of analyzing and interpreting data (P3). Many sets of data need to be created (see Sec. 5.2.1) in the calculation loop. Ultimately, these sets of data need to be analyzed (e.g., visually through a graph or manually through a print statement). For example, consider Excerpt 49 from Group I, where a graph is used to generate meaning in their data:

TA: So if you see that wobble there [points to graph]

TA: And, and so what does that tell you about the orbit?

SB: That its not perfectly circular?

SC: Right that it doesn't go in a perfect circle.

Here, the group is being asked to question the meaning of the sinusoidal data that they have visualized graphically. Given the focus on interpreting data in Weintrop et. al's definition of investigating systems as a whole, we expect to see this practice.

However, one reason that we observe investigating systems as a whole less commonly within our data might be that individuals vary in their levels of curiosity – a crucial characteristic for this practice. Many groups struggle with the details of the problem and spend most of their time focusing on them without taking a step back to question how they relate to the system as a whole. For example, Excerpt 26 from Group F shows an atypical exchange where a group member is taking a step back to check the system as a whole:

SC: But wait is that gonna work up here then?

SC: Wont that break the program?

SC: Because we already have it defined...

SB: No no were not defining it again

SB: We are just using it

Here, Student C is concerned about defining an abstraction in the wrong location and asks a clarification question about its relation to the program as a whole.

Understanding relationships

The practice of **understanding relationships** in a system involves *identifying* the individual elements of the system and *explaining* their relationships to one another. For example, a group might identify the mass and local acceleration due to gravity as the individual elements of the system of the local gravitational force. The group could then explain the relationship between these two elements as they relate to the force (i.e., the force is proportional to both the mass and acceleration). This type of practice was observed 13 times across the data, accounting for 13% of the systems thinking practices, and 4% of all practices.

Understanding relationships most likely shows up in our data given the learning goal of being able to develop and use a model (P1). Developing a model involves an iterative process of creating the model, making predictions with it, and validating the model based on its results [4]. Throughout this process, the individual elements of the system must be identified and correctly related to one another. For example, consider Excerpt 37 from Group

H where they are validating their model based on the relationship between the force and the separation distance:

SC: So right now the force is just always acting in this way in the negative x-direction.

SC: But the force needs to eventually point this way in the negative y-direction...

SB: Okay...

SC: So if we put the satellite dot position down here...

SC: We could make it do that...

SA: Right so let's do that then.

Here, the group has identified the individual elements of the force and the position of the satellite. Further, they are explaining the way in which the two should be related (i.e., an inverse dependence). Given these types of interactions, we expect to observe this practice in our data.

Additionally, understanding relationships likely shows up in our data given that the course is designed to cover multiple force models with widely varying complexity. Specifically, the first week focuses on a constant velocity motion, with a relatively simple constant zero force model. The second week focuses on constant acceleration motion, with a slightly more complicated constant local gravitational force model. The third week focuses on non-constant forces, like the centripetal force and the Newtonian gravitational force, which are general, complex, and difficult to grapple with. Given the complexity of the models used in the third week, it takes a significant amount of time and discussion to develop a strong understanding – which we can then observe.

However, one reason that we observe understanding relationships less commonly within our data might be that some individuals are more and some are less mathematically inclined – one of the biggest factors in success in physics [56, 57]. Having a strong mathematical background with a deep understanding of mathematical relationships in general (e.g., an inverse square relationship) is relatively rare at the introductory physics level, and so we only see this practices less commonly relative to the rest. For example, Excerpt 30 from Group I shows a relatively rare exchange:

SA: So like if you think about making the distance really big...

SA: Since it's in the denominator, if you make that really big...

SA: Then this the force becomes really small.

SA: Which it should right?

SB: Yeah okay that makes sense.

Here, Student A is explaining the concept of a limit in terms of the way that the force should depend on distance (i.e., $F \propto 1/d^2$). Given the rarity of this type of interaction, we expect to see this practice less commonly relative to the rest.

Appendix C

Unobserved practices

The practice of **manipulating data** is not expected to show up in our data given that its definition (see Sec. 2.1) focuses on the reshaping of data (e.g., filtering a set of data or merging two sets of data into one). Students are not required to reshape data in this way in P^3 (e.g., by using the pandas package to merge two data sets). Rather, they are required to create the data algorithmically, which can then be visualized or analyzed.

Any manipulation of data, in its most generous sense, happens at the level of the model or algorithm that is creating the data. Accordingly, excerpts that might generously be considered manipulating data are better classified as creating data (see Sec. 5.2.1). Overall, we don't expect students in P^3 to be able to reshape/clean-up large of sets of data, rather, we want them to be able to correctly create those large sets of data using mathematical and computational models.

The practice of **choosing computational tools** is not expected to show up in our data given that the tool they are required to use it provided to them. The first three MWPs are all implemented through VPython and require no additional tools. Accordingly, by the third problem, students are familiar with the tool and know to take advantage of it.

It should be noted that nothing precludes students from using other tools (e.g., Microsoft Excel) to solve the problem, however we have not observed this in our data. This is likely due to the lack of a learning goal focusing on tool selection. Overall, we want students in P^3

to become proficient with the tool of VPython for modeling motion, rather than being able to choose between competing tools.

The practice of **developing modular solutions** is not expected to show up in our data given that the computational problems from week to week are sufficiently different that new models must always be used. This does not allow for much cross-over or reuse between solutions. Specifically, the first problem involves no net force, the second problem involves a piecewise constant net force, and the third involves a non-constant net force – all being sufficiently different to warrant the construction of unique computational models. This repeated design, construction, and assessment of new models, written from scratch, aligns well with the learning goal of developing and using models (P1). Overall, we students in P^3 to be able to design, construct, and assess new models from scratch, rather than be able to reuse old models.

The practice of **preparing problems for computational solutions** is not expected to show up in our data given that the problem has already been cast in a form that is amenable to a computational solution. In fact, this is the third problem that they have seen like this, so they already know to approach it computationally. Any preparation of a problem, in its most generous sense, happens at the design stage. Accordingly, excerpts that might generously be considered preparation of a problem are better classified as designing a computational model (see Sec. 5.2.3). Overall, we don't expect students in P^3 to generate their own problems (aside from the create your own problem day...), rather, we expect them to be able to solve well-defined problems.

The practice of **defining systems and managing complexity** is not expected to show up in our data given that most students have very little prior programming experience. This is possibly due to the fact that there are no computational prerequisites for P^3. Given this lack of prior programming experience, interaction with the programming system as a whole is restricted by design. Although there is an instructor generated system that students are using (i.e., a MWP in Python that interfaces with PhysUtil and the Visual module), its complexity and management are beyond the scope of the course. This is reflected in the absence of a learning goal (see Sec. 3.4) focusing on the system as a whole. Additionally, the problem statement itself does not explicitly require students to interact with the system as a whole, and tutors will dissuade this action.

Further, the first three MWPs all follow the same basic program structure: using a single calculation loop to integrate Newton's equations of motion with a particular force model. Accordingly, the vast majority of time is spent working on the force model, rather than engaging with the system itself. In this way, we limit the students' interactions with defining systems and managing their complexity. Above all, we don't expect students in P^3 to understand or modify the underlying system itself, rather, we just expect them to be able to use it to solve the problem.

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