Investigation into Students' Understanding of Graphs representing a Qualitative Physics Scenario

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Thesis Submitted for the Award of MSc

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Science is entirely my own work, and that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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List of Publications

- Condon, O., Kelly, T.J., Power, S.J. and van Kampen, P., 2024. Students' scaling of axes when constructing qualitative graphs that represent a physics scenario. Phys. Educ. 59 025001.
- Condon, O., Kelly, T.J., Power, S.J. and van Kampen, P., (submitted to Physical Review Physics Education Research) Students' construction of non-numerical Cartesian graphs corresponding to a hypothetical physics experiment

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Abstract

Graphs are an ever increasingly important tool used in our everyday lives, and yet there is a lack of research in this area. This is especially true in relation to the construction of qualitative graphs. Based on this gap in the existing literature, I decided to investigate first year undergraduate students that were enrolled in a physics module aimed for non-physics majors. My main focus was their thought process when asked to draw a qualitative graph representing a physics scenario.

I developed a series of questions which were issued to students over the past two years. These questions all followed the same format: students were given a diagram of a hypothetical physics experiment and a piece of text describing the situation. They were also given a partially completed graph and then asked what the completed graph would look like. FInally, they were asked to explain their reasoning.

The following text showcases my detailed analysis of the students' responses. I studied all aspects of the collected data, from the spacings they drew on the axes of their graphs, to the language they used in their explanations of why they had drawn the graph as they had. I varied both the context of the experiment (ranging from everyday scenarios to more abstract physics) as well as the way in which the experiment was described (ranging from a brief description to a more detailed explanation).

My research shows that both of these factors, context and level of detail, have a strong effect on students' ability to draw the correct graph. I also found that students who made explicit reference to their graph when explaining it, were more likely to have drawn the correct graph than those who did not. On the other hand, students who mentioned "time" or "friction" were more inclined to draw an incorrectly shaped graph.

1. Introduction

1.1. Motivation for Conducting this Study

My background is Maths and Physics secondary school teaching. I completed a B.Sc. in Science Education in Dublin City University in May 2022. As part of my degree I carried out placements in different secondary schools where I taught maths, physics and junior cycle science to students from 1st year (age 12) to 6th year (age 18). As is their nature, these three subjects all require the use of graphs. In fact, all three of these syllabi contain explicit references to the use of graphs.

My personal interest in graphing dates back to when I was 14 years old in 2nd Year maths. My teacher called my homework, which had been to sketch several different functions, “clear as mud”. I couldn’t understand the issue - all of the functions were drawn correctly, I had simply opted to use different coloured pens and draw them all on the one axis rather than give them each their own. Of course now I can see where he was coming from. Whilst there was nothing definitively “wrong” with my work, it definitely could have been presented a lot more clearly.

In maths, students are typically asked to sketch a graph of a function and they generally do so by calculating some points using the formula and then plotting these on a graph. On the other hand, in science and physics, students typically carry out an experiment and collect their own data. They are then asked to graph this data to investigate the relationship between two variables.

When teaching these students, I was surprised at how poor their graphing literacy skills were. One thing that I noticed was how students would plot individual points and then just connect these points by “joining the dots” rather than drawing a line of best fit or a smooth curve. It seemed that they were just thinking about individual points in time rather than a continuous process, and that they were transforming pairs of numbers to dots on a Cartesian graph. I saw it both inside my maths class as well as among my fifth year physics students. Students are capable of explaining a physics concept and are capable of plotting points on a graph but often struggle to relate the two processes. I realised that if I were to continue teaching, I wanted to learn more about the ways that students approached graphing, so that I could better prepare for how to teach students to avoid these misconceptions from forming in the first place. I decided to investigate how students deal with qualitative graphs, so that I could better understand how they dealt with graphs as a whole rather than just individual data points.

What if students had no numbers to work with, and had no choice but to think about the process? I wanted to see how students tackled graphs involving non-quantitative scenarios as this would help me to gather more insights into their general understanding of graphs. I asked students to complete the distance versus time graph shown for a ball rolling down the tracks in Figure 1.1.1, and the water-level time graphs for the beakers shown in Figure 1.1.2. I also asked questions relating to the resistance along a wire, however for the purpose of this thesis I have opted not to focus on those cases (as the underlying physics concepts were more complex and may have impacted the results). Along with the images, I gave students a textual version of the scenario: e.g. a ball is released from the top of a ramp and rolls along a frictionless track with three evenly spaced points. Students were asked to complete the graph, and explain their answer. To do this successfully, students must think of the end point on both axes, and what shape the graph should have. As detailed in Chapter 2, qualitative construction tasks like these have not been researched often and can prove difficult for students. On the other hand, if students can construct a graph in this manner, it is good evidence that they have a comprehensive understanding of graphing a physics scenario.

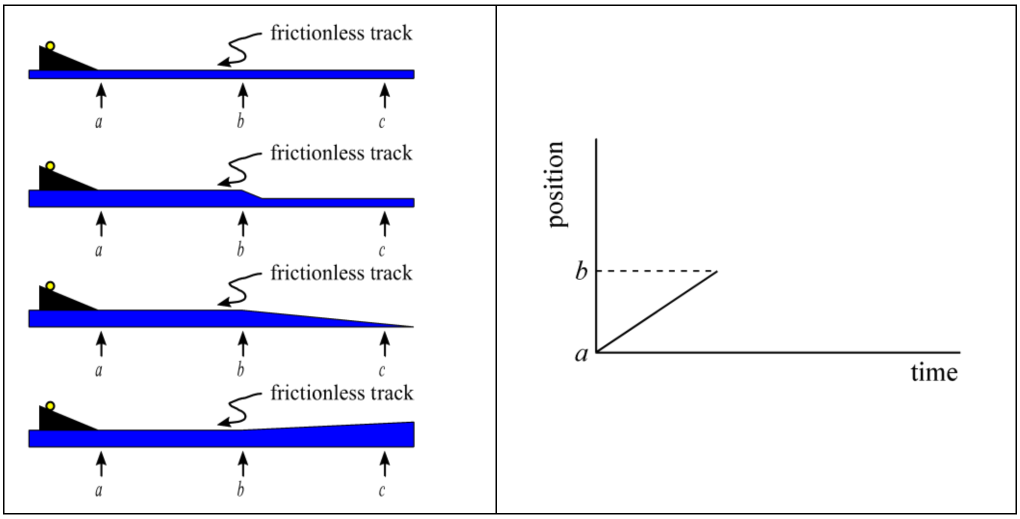


Figure 1.1.1. Images used in qualitative questions about tracks.

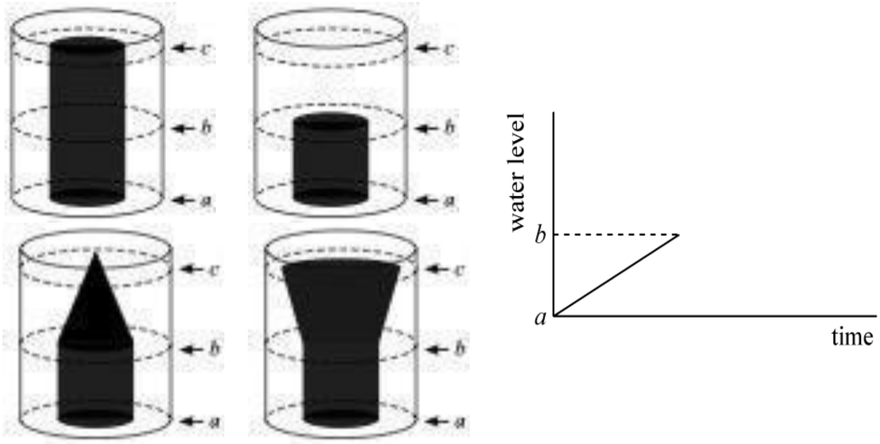


Figure 1.1.2. Images used in qualitative questions about beakers.

I approach this project from a constructivist perspective, understanding that a student's knowledge is not just information that they have passively obtained, but rather gathered over time throughout active participation. It is a product of both experience and prior knowledge, and grows with the student as they learn in stages. My constructivist belief featured prominently in the design and implementation of this project.

1.2. Aims and Objectives and Significance of the Research

The research was carried out in an Irish university with first year undergraduate students. The students were non-physics majors enrolled in either one or both of two modules, Physics for General Science I and Physics for General Science II, which are first-year modules that comprise of lectures and labs. Physics for General Science I runs in semester one and Physics for General Science II runs in semester two and they have different content and syllabi (but related with the semester two module content following on from semester one). Based on the needs of their degree programmes some students only took the semester one module, while others took both modules. As such, the semester two module has a smaller class size, and I therefore had a smaller sample size for questions administered in the second semester. The students were all enrolled in STEM based degrees and would therefore be expected to have a high level of graphing literacy. Whilst I am primarily coming at this from a physics perspective, I am a qualified maths teacher, and as graphs are naturally a part of mathematics too, I intend to use methods and literature from both disciplines.

The research was carried out over two years with a large group of students (circa 800). This enabled the class population to be split into smaller groups which allowed me to ask different questions to see what effect context or wording had on a student's ability to correctly answer the question, while maintaining large enough sample sizes to ensure statistically significant results.

The purpose of this study is to investigate students' thought processes when attempting problems relating to graphs, specifically the construction of qualitative graphs. Our research aims to analyse the strategies that students employ when facing the kinds of problems shown in Figs 1.1 and 1.2. The two scenarios allow us to check if context affected the methods students employed when answering these questions. This would show us if different approaches should be used when teaching more abstract physics concepts compared to more everyday scenarios.

When we investigate students' approaches, we think in terms of *resources*, pieces of knowledge that students have, activate, and coordinate to solve a problem. The purpose of this study is to better understand the resources that students activate and the techniques that they employ when faced with a graphing problem. I varied the way the questions were asked to see if there is a difference in what is triggered and what trajectory students followed when thinking about a problem. If we better understand the ways that students think, then we can better plan ways to teach them so as to ensure their full potential is realised.

1.3. Research Questions

Following the literature review, and after establishing that students have difficulties in understanding and constructing graphs, I decided to focus on the construction of qualitative graphs, as this area remains largely under researched. This led to the formulation of the following research questions.

RQ1. How do students represent intervals on an axis of a qualitative graph?
RQ2. To what extent does context affect the type of argument students use to explain their reasoning?
RQ3. What do students consider when tasked with drawing qualitative graphs?
RQ4. Does the use of certain resources make students more likely to reach the correct answer?

1.4. Research Phases

Project Timeline

Ethical Approval

1

- Ethical Approval was obtained from the DCU Research Ethics Committee
- This included submitting a plain language statement and informed consent form

Literature Review

2

- A thorough literature review was carried out to help further define the project goals

Questions

3

- The class was split into groups based on timetables
- A different set of questions was administered to each group

Data Analysis

4

- Responses were first analysed based on the shapes students drew
- Their written responses were then analysed to look for predictive indicators

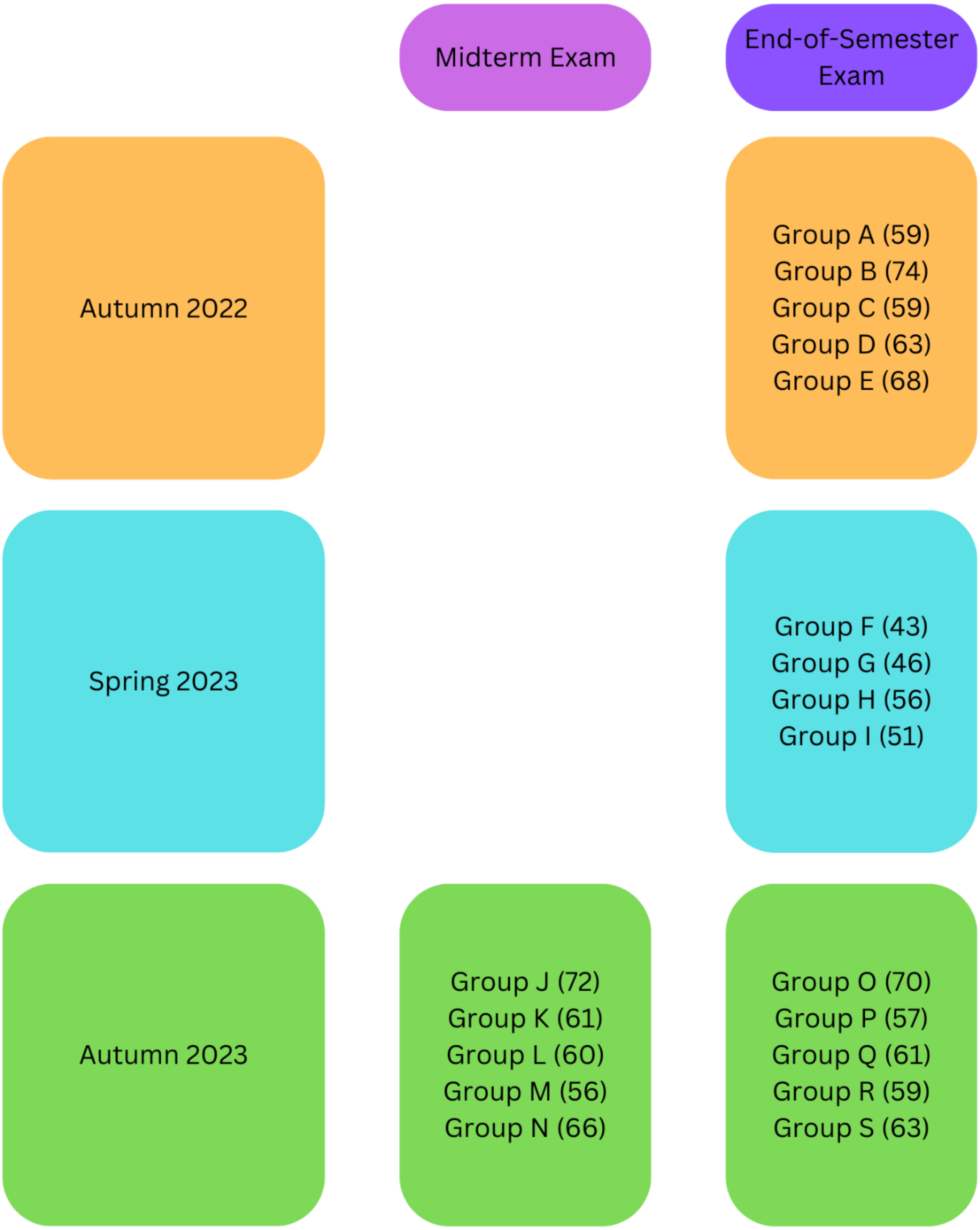
Findings

5

Examples of where my findings were presented:

- CASTeL Lunchtime seminar
- X-DBER Conference
- DCU School of Physics Day
- MEI Conference

- After preliminary analysis, questions were reformatted



Timeframe of Questions

	Midterm Exam	End-of-Semester Exam
Autumn 2022		Group A (59) Group B (74) Group C (59) Group D (63) Group E (68)
Spring 2023		Group F (43) Group G (46) Group H (56) Group I (51)
Autumn 2023	Group J (72) Group K (61) Group L (60) Group M (56) Group N (66)	Group O (70) Group P (57) Group Q (61) Group R (59) Group S (63)

Figure 1.4.1. Timeline of when different questions were administered and to which students.

2. Literature Review

2.1. Overview of graphing education literature

Research on students’ graphing abilities has been carried out for many years, highlighting its significance and importance. In fact, research on graphing has been carried out from the very early days of science and mathematics education research. Two overviews that cover the early literature in this area are those by Leinhardt *et al* (1990) and Glazer (2011). Most of the research, however, tends to focus on students’ interpretation of graphs, or, in the cases where construction is involved, on quantitative graphs. In what follows I will discuss existing literature that highlights science education and mathematics education research about student understanding of qualitative graphs.

Examples of this early research include work by Kerslake (1977) who examined students' ability to interpret qualitative graphs. Their research involved secondary school students and found that a very large number of students had trouble interpreting qualitative distance-time graphs. For example, one particular question presented students with three qualitative distance-time graphs (Fig 2.1.1.). Students were first asked if the graph represented a journey, and then were asked to describe the journey. As the students got older, the percentage of correct answers increased, however, so too did the percentage of students that misinterpreted the graph as a map of the journey: for example, the bottom graph of Figure 2.1.1. would often be interpreted as going up and down a hill. In fact a larger number of students misinterpreted the graph as graph-as-picture than those who correctly interpreted it. I later see this in my own work, with a larger number of students drawing the same incorrect graph than drawing the correct one.

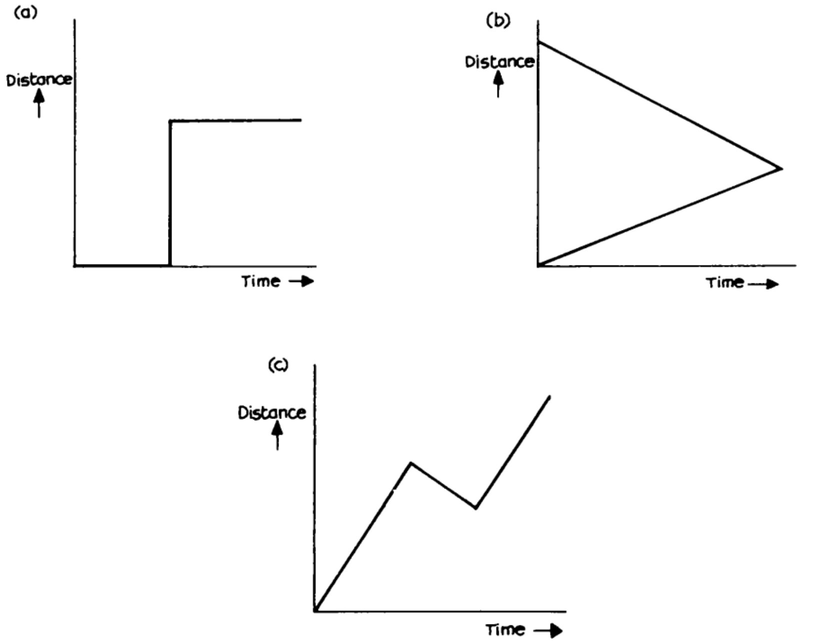
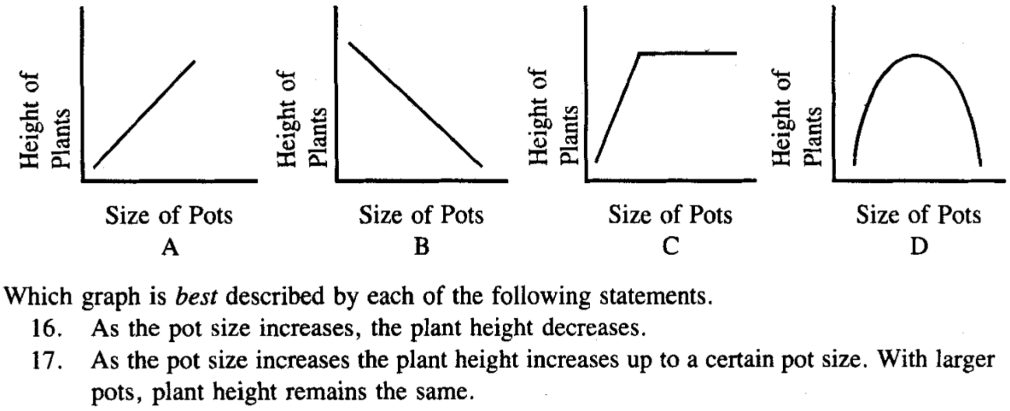


Figure 2.1.1. Qualitative distance-time graphs used in Kerslake (1977).

Beichner (1994) gave students several questions where they were asked to interpret position vs time, velocity vs time and acceleration vs time graphs. He referred to this as a Test of Understanding Graphs in Kinematics. The TUG-K test has been used by many researchers as a method of analysing student understanding in this area. The test showcased several challenges that students faced, including: slope/height confusion (not knowing whether they could just read the y-coordinate or a calculation was required), variable confusion (uncertainty regarding the x and y axes), and difficulties in finding the slope of a line not starting at the origin (dividing the y coordinate by the x coordinate instead of taking the interval on each axis). The research also found that similar to Kerslake's work, students have a tendency to treat the graph as a picture.

Some other examples of early research in this area include work by McKenzie and Padilla (1986) who created a Test of Graphing in Science (TOGS) which contained a series of problems including one that asked students to interpret qualitative graphs of plant height vs pot size. Here they were given four different graphs and two qualitative statements and asked which graphs the statements could be referring to (Figure 2.1.2). Again it was shown that students really struggle to understand qualitative graphs.



Which graph is *best* described by each of the following statements.

16. As the pot size increases, the plant height decreases.
17. As the pot size increases the plant height increases up to a certain pot size. With larger pots, plant height remains the same.

Figure 2.1.2. Qualitative graphs used by McKenzie and Padilla (1986).

In McDermott *et al*'s work (1987) it was found that students have a lot of difficulties when asked to relate qualitative graphs to both physical concepts and to the real world. Here again we can see that many students misinterpret the graph as a picture. One question provided students with a qualitative position vs time graph and asked them to draw a corresponding velocity vs time graph. Here a common wrong response was an inversion of the original graph, which suggests that students place a high value on the shape of a graph, once again highlighting the difficulties students face in dealing with qualitative position-time graphs.

In terms of literature referring to the construction of graphs, I found that the vast majority of existing research deals with the construction of quantitative graphs, usually involving the use of tabulated data. One example of this type of research is that carried out by Tairab and Khalaf Al-Naqbi (2004). They asked a series of questions including both interpretation and construction tasks, however these construction tasks involved the students using a provided table of data to then draw a Cartesian graph. Other examples of work relating to construction of quantitative graphs can be found in work by Kerslake (1977), Karplus (1979) and Johnson (2015).

As previously stated, construction of qualitative graphs is under-researched, however there are a few noteworthy examples. Mevarech and Kramarsky (1997) provided eighth grade students (aged 13-14) with four statements of a qualitative nature. These statements related the amount of time spent studying to how well a student performed on an exam. Students were asked to construct graphs for these qualitative statements. They were not specifically told to draw Cartesian graphs. The study showed that these students came to class with preconceptions about graphing despite not having a formal education. Prior to instruction, approximately 25% of the students correctly transformed all four statements into a graph. The study goes on to state that after instruction, many students still held on to their alternative conceptions and that they were reluctant to change their thinking. This shows that students possess preconceptions that can be very difficult to change.

In their 2012 work, Hattikudur *et al* investigated students' ability to construct graphs when given a written prompt of both qualitative and quantitative natures. Their work had a specific focus on how accurately students plotted the *y*-intercept and the slope. Their research showed that students have more difficulty in understanding the *y*-intercept than the slope. This is especially true in the case of qualitative statements.

Van den Eynde *et al* (2019) investigated what effect context has on students' ability to translate back and forth between equations and graphs. This was investigated by presenting students with 8 qualitative graphs and an equation and asking them to explain which graph the equation represented. The reverse of this was to present one qualitative graph alongside 8 equations and again ask them to explain which equation corresponded to the graph. They established that students are more capable of correctly translating between graphs and equations in a mathematical context than they are in a physics context. This work was carried out with students of the same general background and education as those involved in my study.

Moore and Thompson (2015) introduced the concept of "shape thinking" as a way to examine how students think of graphs. They described two different ways of thinking about graphs, which they labelled as "static" and "emergent". The basic difference is that static thinking involves thinking of the graph as though it were an object, whereas emergent thinking recognises that a graph comprises both a trace (what is made) and a level of covariation (how it is made). Their research found that emergent thinkers were better able to switch between multiple representations.

Moore (2016) expanded on this earlier work by delving into the thought processes students engage in when tasked with drawing graphs. Building on Piaget's work, he distinguished between operative and figurative thought. Generally speaking, figurative thought pertains to observable, measurable, "real" properties like the colour of an object; operative thought pertains to abstractions and interpretations, such as "red means danger". In this paper, Moore expands on his previously defined "static" thinking to include aspects of figurative thought. Moore states that based on the fact that cognitive development can be considered as a movement from figurative thought to more operative thought, one would imagine that college students have progressed towards a more operative way of thinking about graphs. However, his research showed that this is not the case.

2.2. Resources

Constructivism, the theory that conceptual understanding is generally not acquired passively but constructed through social and cognitive experiences, comes in many different forms. Elby (2000) made the distinction between misconceptions constructivism, where students are seen as having more or less coherent and robust misconceptions that should be changed, and fine-grained constructivism, where students are seen as having loosely connected elements of knowledge that are used in the moment. A prominent example of the latter is diSessa’s (1988, 1993) “knowledge-in-pieces” model as part of trying to develop an epistemology of physics. He was trying to better understand how students intuitively think about physics, and how this affects their ability to learn physics in a formal setting. The most basic elements, or building blocks, involved in knowledge-in-pieces are referred to as phenomenological primitives (p-prims). These are directly related to observable phenomena and tend to involve a very basic explanation. An example of a p-prim is “closer means stronger”. Understanding how students form and utilise these p-prims is an important step in understanding the knowledge in pieces theory. This in turn can help teachers to better understand how students think about physics which will in turn help them to become more effective teachers.

Resource theory is a theoretical framework which builds on diSessa’s work. The idea is that everyone possesses a collection of cognitive units which are activated when given prompts and which connect to each other in flexible networks. These cognitive units are considered to be fine-grained “resources”. Resources can be thought of as a step above p-prims in that they are less primitive and contain more depth. Resources tend to build on p-prims and can group them together. Examples of some existing research in this area are listed below.

Hammer (1996) is one of the earlier researchers to develop and apply resource theory to physics education. In this paper he discusses the differences between student misconceptions and phenomenological primitives (p-prims). Early physics education research has primarily focused on misconceptions that students bring to the classroom from past experiences, whereas diSessa’s p-prims deal with smaller fragments more in line with the knowledge-in-pieces theory.

Hammer (1996) takes an excerpt of dialogue that occurred in an American high school physics classroom and analyses it under different theoretical frameworks and perspectives. These include misconceptions and p-prims - perspectives featured in Hammer’s other work. The purpose is to analyse the students’ understanding in ways that their teacher might.

Hammer (2000) decided instead of focusing on student misconceptions, as was the norm in physics education, to focus on student resources involved in learning. Hammer splits the students' resources into two categories, deemed conceptual and epistemological resources. He acknowledges that this is just an early step in the understanding of student resources and that more research needs to be carried out to better inform educators on how best to help students reach their full potential.

Hammer *et al* (2005) discuss how students apply resources to different contexts. They briefly use the term “transfer” before claiming that it is too hard to clearly define and instead prefer to talk about the “activation” of resources. One reason to avoid the term transfer is that it treats knowledge as a tangible thing that can be relocated, whereas resource theory treats it as small pieces that interlock and affect each other when one is activated. Hammer *et al* shows examples of real students and compares the students’ thought processes under both frameworks.

Robertson *et al* (2021) examined the resources students employ when given conceptual physics questions relating to forces. They established six common conceptual resources that physics students used when attempting to answer conceptual questions. Many of the resources are generalisations of physics laws. The authors explain how resource theory centres around the idea of activating and reorganising resources to form connections and further learning.

Rodriguez *et al* (2018) looked at how students reason mathematically in chemistry. They used the resources framework as a theoretical lens through which they can examine the students' thought processes. This paper focuses on four students and looks at how these students engage in “blending” resources from different subjects to reach their conclusion. The study showed that students must be competent in using symbolic and graphical forms of reasoning if they are to successfully merge chemistry and mathematics.

Parobek *et al* (2021) used resource theory to analyse students’ reasoning in the field of chemistry. They interviewed 16 students in a semi-structured manner and then applied the resource theory framework to their collected data. This study aims to better understand how the activation of different mathematical resources can cause students to then activate resources that are more specific to the chemistry question at hand.

Bain *et al* (2019) also looked at how students activate and utilise their mathematical resources when faced with a chemistry problem. This paper specifically aimed to investigate students’ understanding of the term “constant” in the context of chemical reactions. They categorised students' resources according to the “level of sophistication” of the argument that the resources produced, showing that the activation of certain resources led to a more coherent, well-structured argument than others, and allowing them to focus on what students know rather than don’t know.

Rodriguez *et al* (2020) also focused on chemistry education and studies how students interpret and utilise graphs when asked to reason about a varied population. It was found that whilst students have useful resources to discuss the problem in general terms, their resources are not always activated when they are asked to interpret a graph. This paper used resource graphs as a method of visualising students’ resources and understanding of the topic. These resource graphs are a map of each student’s resources with connections between the elements that relate to each other.

2.3. Reasoning Chains

“Reasoning chain” is the term coined to describe the way that students link together elements of reasoning in a chain-like fashion before reaching a conclusion (Speirs *et al*, 2016). The idea of a reasoning chain is compatible with that of resources: a reasoning chain is the end product of how students activate and coordinate resources.

Speirs *et al* (2016) examined students' abilities to create a well-structured reasoning chain. Physics students were given a problem along with various true reasoning elements and were asked to order these elements to form a coherent reasoning chain for the problem. Results showed that student performance in this "chaining task" did not differ significantly from a more "traditional" format, which suggests that even when being given the "correct" reasoning elements, students can still form incorrect conclusions.

Lindsey *et al* (2023) researched how capable students are at following a given deductive reasoning chain and reaching the corresponding conclusion. Students were presented with a physics problem and asked to explain their reasoning. Then they were given a fictitious reasoning chain and asked to select the appropriate conclusion to that chain. The results show that when given a reasoning chain, students are typically very capable at following the chain and reaching the appropriate conclusion. However, the research also showed that generally speaking, students do not use first principles and form reasoning chains of their own.

Johnson (2017) studies the effect that the "direction" of the question has on students' abilities to construct inferential reasoning chains. Some students were given an outcome and asked to establish how the variable changed to reach this outcome while others were given the changes the variable underwent and asked to explain what would happen to the outcome. In other terms, some students were given a process, while others were given the end product. It was found that in certain contexts, the direction of the question has a large effect on student performance. Whilst this was not true for all scenarios, it validated my research question to see what effect context has on student performance.

2.4. Implications for this study

This thorough examination of the existing literature showed me that students' reasoning on qualitative graphs is often based on interpretation of given abstract graphs rather than construction. It is typically captured by descriptive statistics or a typography of student responses. The research shows that students at all levels of education have various difficulties with graphing. The most prominent of these are graph-as-picture interpretation and slope-height confusion. Students find it hard to connect graphs to equations and to real-life situations. Students' understanding of graph construction and qualitative graphs seem to be under-researched areas.

In teaching and learning physics, connecting graphs to the reality of a physics experiment is important. Being able to engage in qualitative reasoning, without the support of calculations that can mask conceptual difficulties, is often an indication of deep understanding. For this reason I chose to focus on students' ability to construct qualitative graphs representing different hypothetical physics experiments, and to explain their reasons for constructing the graph the way they did. Our analysis spans both descriptive statistics, in line with my fine-grained constructivist stance, and a more fine-grained analysis of the reasoning elements students use. Following careful reading of the existing research, I decided to investigate what role the hypothetical experimental context plays in students’ ability to construct a qualitative graph of a given scenario. As my research progressed, I decided to investigate what effect the wording of a question has on student performance. This was in part to see if different phrasing or question format would affect the resources that students employed.

As will become apparent in Chapter 4, some reasoning chains students used in their responses seem to map onto the ideas of emergent and static thinking based on the graphs that they drew and the explanations they provided; for example whether students would talk about speed (static) or acceleration (emergent). However, whilst interesting, I decided to focus more on reasoning chains and to leave shape thinking for future studies.

3. Methodology

3.1. Introduction

This chapter describes the methods that I used throughout this study. I first provide an overview of the timeline of the project and then explain why I thought this methodology was most appropriate.

3.2. Timeline

Table 3.2. provides a brief chronological overview of the main milestones and key events that formed this project.

Table 3.2. Project milestones.

Date	**Activity**
Sept 2022	Ethical Approval applied for and obtained
Sept-Nov 2022	Lit Review and Composing of Questions
Dec 2022	Administered three Tracks and two Beakers questions (A,B,C,D,E)
Jan-Mar 2023	Initial Analysis and Formation of Wire Questions
Apr 2023	XDBER Conference
Apr 2023	Administered four versions of Wires questions (F,G,H,I)
Oct 2023	Five Tracks (J,K,L,M,N)
Oct 2023	MEI Conference
Dec 2023	Five Beakers (O,P,Q,R,S)
Dec 2023	Two Student Interviews
Jan 2024	Publication in Physics Education Journal
Jan-May 2024	Analysis and Writing of Thesis

3.3. Ethical Approval

One of the first milestones in this project was to obtain ethical approval from the Dublin City University Research Ethics Committee (REC). This involved completing a form outlining various aspects of the project, including a data management plan, results dissemination plan and contingency plans should any issues arise. I provided the aims of the project as well as an outline of the methodology that would be used to achieve these objectives. I also described the profile of the participants and discussed any potential risk factors. To reduce the risk on students, I decided that all student responses would be anonymised before being analysed. Students were made aware that their work would be completely anonymous and were given the opportunity to opt in to being a part of the study with no onus on them to do so. I also submitted a plain language statement and an informed consent form that would both be given to the students prior to collecting any data. A few weeks later, after the board had met, I received approval from the REC and were given the go ahead to begin the project.

3.4. Research paradigm

There are two main categories that data can be classified into: quantitative and qualitative. Quantitative research is linked to the research paradigm positivism while qualitative research is associated with the research paradigm interpretivism. Creswell (2002) distinguishes between the two by saying that quantitative research measures quantities and can be used to test existing theories, whilst qualitative research deals with data that cannot be easily measured, and aims to develop a deeper understanding for specific cases as opposed to the generalizability of quantitative research.

The paradigm positivism relies on experiments and observations where measurable data is collected and analysed. For this reason it is largely linked to quantitative data. Some of the methods used in positivism are better suited to studying phenomena in the natural world and are not easily transferred to studying the social world (Alharahsheh and Pius, 2020). Another paradigm similar to positivism is post-positivism. Dawadi, Shrestha and Giri (2021) distinguish between positivism and post-positivism by claiming that positivism is solely objective whereas post-positivism utilises both quantitative and qualitative research methods to allow for some subjectivity.

On the other hand, interpretivism tends to deal with qualitative data. Interpretivism differs from positivism in that it is more subjective and does not attempt to establish rules that can be generalised to multiple scenarios. It aims to develop a deep understanding of social subjects rather than the natural world. It is less about having a general rule that covers a population, but rather a rich understanding of specific cases.

For this project I have chosen to apply a mixed-methods approach where I will employ both qualitative and quantitative research methods. The written responses that I collected from students were rich and full of detail, so I wanted to use qualitative research methods to ensure that that richness wasn’t lost during analysis. However, that being said, I also wanted to ensure that my findings were representative of my large cohort of students, and that they could be applied to students in other scenarios. Therefore, I also used some quantitative research methods in this study. For this reason, I have decided to use both positivist and interpretivist methods in my research.

3.5. Participants

The data gathered for these studies was collected during the 2022-23 and 2023-24 academic years in Dublin City University. The participants (~800) involved in this research were all first-year undergraduate students. They were all non-physics majors and were enrolled in a physics module for non-physics students with a lecture and a lab component. Due to the size of the class, the available laboratory space, and the students' timetables, the class was split into five different lab sessions in semester one, and four sessions in semester two.

When assigning different questions to different students I used convenience sampling and used the groups the students were already split into (the class was too large for the laboratory, so the same session was repeated to accommodate different groups of students). This means that within each group, the students had a similar background, as the students were grouped according to their degree path (where possible). All students in the module were asked to answer the questions as part of their assessment, but they were given the option to abstain from letting their responses be analysed as part of this research.

3.6. Data Collected

The data collected throughout this study is qualitative in nature. However, I quantified the data so that I could perform quantitative analysis. This allowed me to use descriptive statistics (measures of frequency) to look for trends in the student responses. It turned out that I was able to code much of the data dichotomously, i.e. into two categories, which allowed us to perform a logistic regression on the data.

Students were asked to draw graphs and to provide a written explanation as to why they had chosen to draw them in that way. The graphs drawn by students are qualitative in nature as they were not given any numerical data to work with, but rather a qualitative statement and a diagram as shown in Figure 3.7.1.1. I carried out qualitative analysis on the students' responses and developed a codebook. This codebook was used to categorise the responses. It was based on the student responses, but informed by both my fine-grained constructivist stance and the theory described in Chapter 2, especially the ideas about static and emergent graphs by Moore and Thompson (2015). I then carried out numerical analysis to establish what proportion of students gave each category of response. This was also then used to see if certain written responses were predictors of whether or not the student would draw the correct graph.

3.7. Research Instruments

3.7.1. Questionnaires

The primary research instruments used throughout the course of this project were questionnaires administered to students as part of a midterm/end-of-term examination. The first set of questions consisted of five different hypothetical experiments (given to five different groups of students) and asked students to draw a graph representing the experiment and explain their answer.

The choice of the questions was informed to some extent by the setting. Because they were part of a laboratory exam, the questions needed to refer to an experiment. This gave us an opportunity to invite the students to visualise covariation through the narrative (the position of a ball with time as it rolls along a track, the water level with time as the beaker is filled, the resistance between two probes as one of them moves along a wire), and to see if this covariation would be reflected in the explanations of how the students drew their graphs, including if this was static or emergent (Moore and Thompson, 2015).

The questions were completed on paper by the students as part of a midterm/ end-of-semester exam. They were then scanned and anonymised before I was given their responses and began my analysis. Students could opt out of allowing me to analyse their anonymised responses. A preliminary analysis of the responses suggested that students generally understood what the questions asked them, and that different kinds of reasoning could be distinguished. However, we were concerned that in some cases an incorrect graph might reflect an incorrect representation of correctly understood physics, or a correct representation of incorrect physics. To try and delve deeper, I formed a new set of questions to give to students in the following semester.

In later iterations of the questionnaires, I presented students with the same hypothetical experiment but phrased the question differently to see what effect wording had on student performance. Table 3.7.1.1. shows the type of questions that each group was given. All of these questions can be viewed in the appendix, but for convenience, I have included two examples in Figures 3.7.1.1. and 3.7.1.2. of groups C and N, so that the normal vs detailed versions can be compared.

Table 3.7.1.1. Overview of question versions.

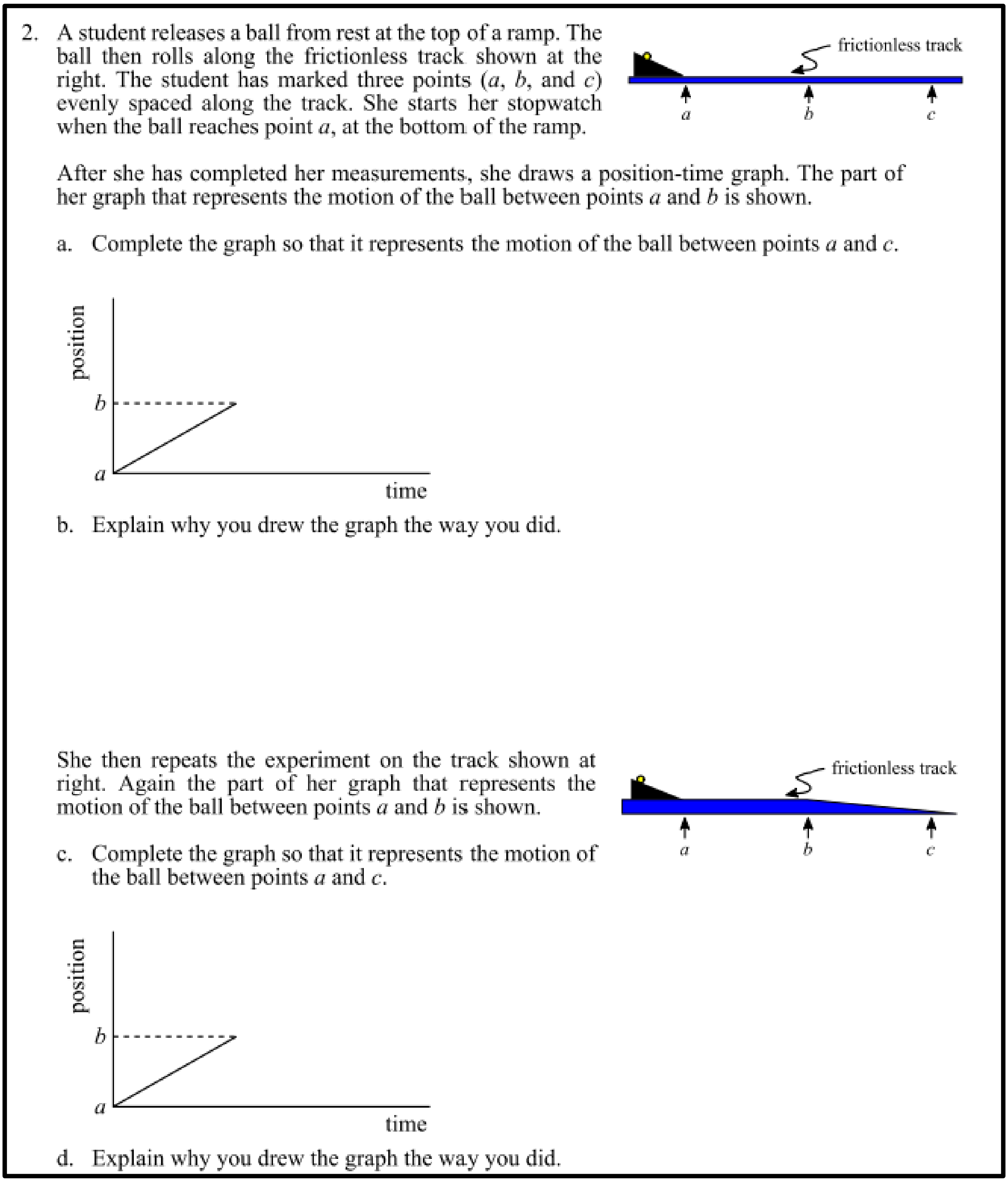
Label	***N***	**Type of Question**
A	59	Step-down Track
B	74	Half-cylinder in Beaker
C	59	Downward Sloped Normal
D	63	Narrowing Cone Normal
E	68	Upward Sloped Normal
F	43	Horizontal Normal
G	46	Vertical Normal
H	56	Horizontal Detailed
I	51	Horizontal MCQ
J	72	Downward Sloped MCQ
K	61	Upward Sloped Explain First
L	60	Downward Sloped no ramp at start
M	56	Upward Sloped Detailed

N	66	Downward Sloped Detailed
O	70	Narrowing Cone Detailed
P	57	Expanding Cone Detailed
Q	61	Narrowing Cone Explain First
R	59	Expanding Cone MCQ
S	63	Expanding Cone Explain First MCQ

Within each context of question (i.e. tracks, beakers, wires), the first part began with the same basic question, where the student would have been expected to draw a straight line continuing the slope of the partially completed graph. This was followed by an alteration to the experimental setup, which is how the groups got their names based on this change. On each image of the experimental setup, three points, a,b and c, were marked so that |ab|=|bc|. Points a and b were included on the position axis of the partially completed graphs. I later refer to |ab| and |bc| on the graph as intervals.

The difference between the groups ending in “normal” and those ending in “detailed” is that the “detailed” groups were given a more descriptive narrative that explicitly stated what was observed throughout the experiment. This was to see if being told precisely what was happening made it easier for students to draw the correct graph.

These variations of questions were chosen as they will provide the data needed to answer my research questions set out in Section 1.3. Asking questions about tracks, beakers, and wires will allow me to investigate the effect that context has on students’ thought processes whilst rewording the questions within the same context will help me to learn more about how phrasing can affect student performance.



2. A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp.

After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

a. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

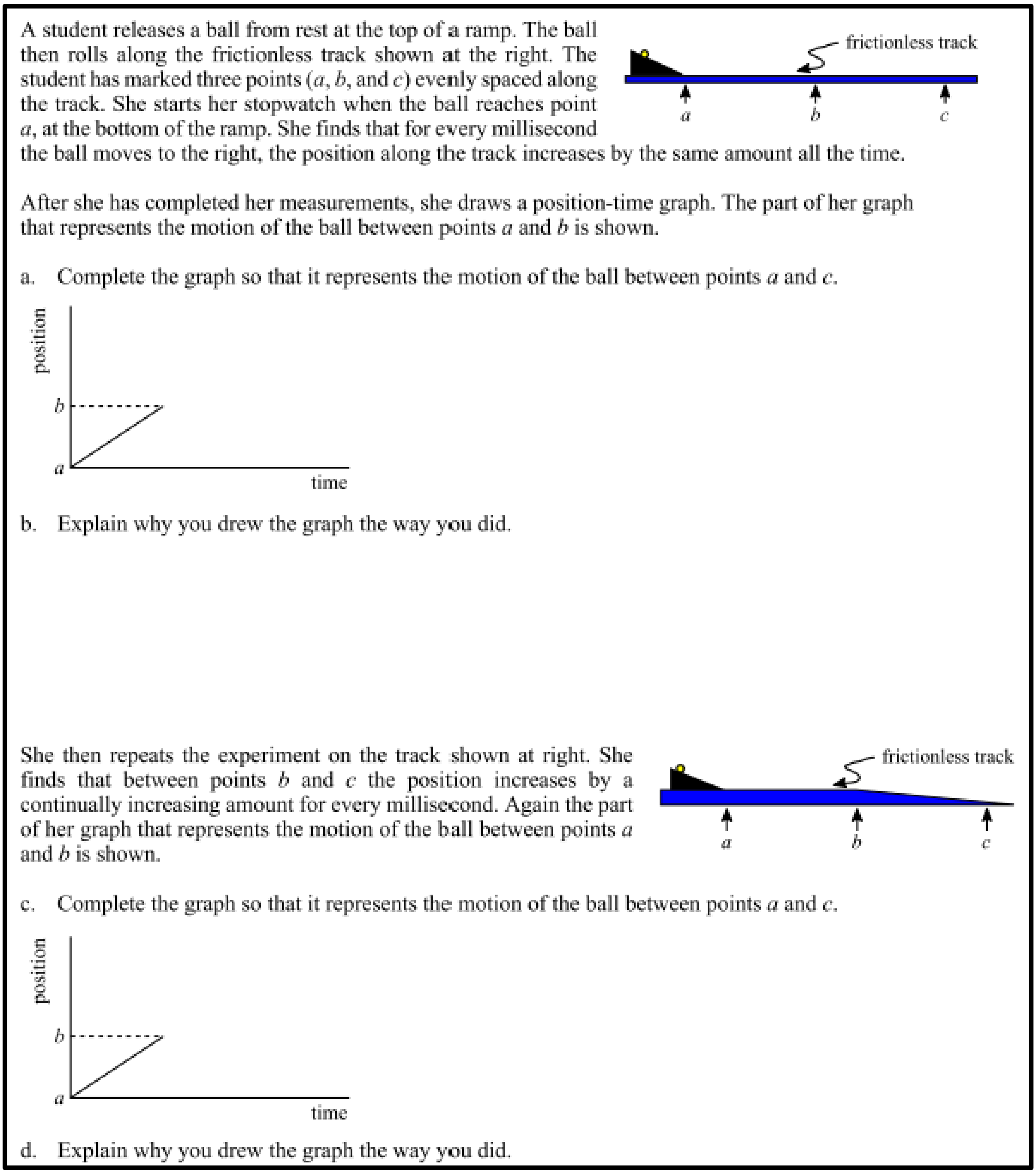
b. Explain why you drew the graph the way you did.

She then repeats the experiment on the track shown at right. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.

c. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

d. Explain why you drew the graph the way you did.

Figure 3.7.1.1. Normal version of downward sloped track question.



A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp. She finds that for every millisecond the ball moves to the right, the position along the track increases by the same amount all the time.

After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

a. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

b. Explain why you drew the graph the way you did.

She then repeats the experiment on the track shown at right. She finds that between points *b* and *c* the position increases by a continually increasing amount for every millisecond. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.

c. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

d. Explain why you drew the graph the way you did.

Figure 3.7.1.2. Detailed version of downward sloped track question.

3.8. Analysis methods

3.8.1. Coding graphs

In the first part of this study I analysed the intervals students drew on their graph, by checking where/if they had plotted the point *c* on their axis. I categorised each graph into same interval / different intervals / no interval depending on how |*ab*| related to |*bc*|. I was satisfied that every graph could be sorted into one of these three categories. I note here that if the intervals looked similar, they were categorised as equal. I did not see evidence that any student used a ruler to measure equal intervals on the axis.

In the second part of the study, I analysed each graph according to the shape the students drew. I initially formed seven categories: continues slope, parallel slope, flatter line, steeper line, upward curve, downward curve and other. These categories relate the partially completed graph given to the students, with the line that they continued to draw. Figure 3.8.1.1. shows a student sample of each category of graph.

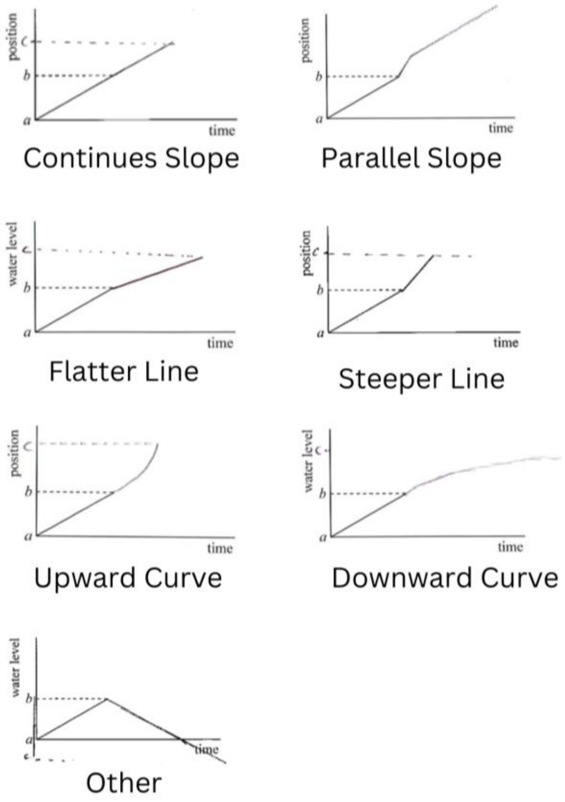


Figure 3.8.1.1. Sample graph of each category type.

The students' written responses were first categorised based on the types of argument in their explanation. When I first read through the students’ written explanations, it struck me that most students referred to either a general overview of the experiment, specifically what happened at point b, or how the process ended. I clarified these three scenarios into the following categories: overall trend, (initial) rate of change, interval to be covered. As I sorted the answers into these three categories, I decided to break each into three subcategories depending on the type of argument the student gave. The three subcategories were: Graphical (direct connections to the graph they drew), Physical (direct connections to physics concepts) and Experimental (direct connection to the hypothetical experimental apparatus). While coding the data, I decided to include another category called Mechanism which was for when students mentioned gravity or external forces. The idea wasn't to sort each response into one category, but rather to take a response and go through each category one by one and indicate whether or not that type of argument was present in the student's explanation. Each answer was coded with a 1 or a 0 for all ten categories depending on whether or not that type of argument had featured in their explanation. This coding emerged from the data, but it was informed by our fine-grained constructivist stance. We sought to identify what knowledge elements students used in their answers, and whether this included a sense of mechanism.

For each of the categorisations of the written responses, a codebook was developed. After a primary analysis of the data, I developed the first version of the codebook. Myself and one other researcher would then code a sample of the data independently and then compare our codes. When there were discrepancies, we discussed our answers and refined the codebook before coding a new sample and repeating the process until a high level of agreement was achieved. For this codebook, I phrased each code as a question of the form "do they mention…?". As an example, the code for (initial) rate of change at b, graphical is: "Do students compare their line to the initial line by using words such as: it got steeper/flatter/sharper, it curved up/down?" The full code book is shown in Appendix A.

I then coded each response based on what elements/resources featured in the explanation. This was because we deemed our first coding scheme rather phenomenological and thought that it focused more on *what* the students did as opposed to *why* they did it. This second coding scheme was an attempt to further our understanding of students' thought processes. I was able to select seven key elements that covered the students' responses without reducing their answers too much: graph, speed, acceleration, and time were common to both track and beaker groups. For tracks I also used friction, slope, and gravity, whilst for the beakers I instead used constant flow, object shape, and volume.

The next step was to identify how students put a structure on these elements. Here I used the idea of reasoning chains developed by Speirs *et al* (2016). Originally the reasoning chains were based solely on the sequence that students had mentioned the elements. This led to a very large number of chains, and some of these seemed very similar. Therefore, in a second step, we imposed some structure to the chains. For example, if students mentioned the graph, that element was put at the end of their reasoning chain, regardless of when the student mentioned it. It seems clear that the graph cannot affect the other elements, but is rather the affected element. We called these standardised orderings *equivalent reasoning chains*.

An example of a student response is:

> *“I drew the graph like this as once it reaches point b the marble begins to move up a slope which causes gravity to act upon it and the marble gradually decelerates at a rate dependent on the angle of the slope. Therefore its speed will decrease and eventually reach 0 before rolling back down the slope.”*
> Group E Student 7

I coded the above responses to form the following equivalent reasoning chain:

> shape so gravity so acceleration so speed so graph

3.8.2. Categorising graphs - intervals

For this part of the study, initially 323 students enrolled in a semester one module were split into 5 groups (A,B,C,D,E). I gave two of these groups a set of questions relating to water flowing into a beaker and the other three groups a set of questions about a ball rolling along a track. In the following semester, I split 145 students into 3 groups (F,G,H) and gave each group a variation on a set of questions about the resistance along a wire. All questions were administered as part of an end-of-semester exam.

With the track and beaker questions, I wanted to keep them as analogous as possible and of a similar standard of difficulty, so that one could see what effect context plays on how students respond. For example I equated the upward sloped track with the narrowing cone beaker group as in both of these groups the process gradually slows down so one would expect students to draw a downward curved graph. Similarly I equated the downward sloped track with the expanding cone, as in these cases the process speeds up and so one would expect students to draw an upward curved graph. Due to logistical reasons, and wanting large enough sample sizes, it was not possible to form a 6th group to pair with the downward sloped track questions.

All three track groups were given the same initial setup - a ball was rolling along a horizontal frictionless track. They were given a partially completed graph of distance vs time and asked to complete it. The diagram of the track had points a, b, and c marked at equal intervals along the track. Points a and b were included on the distance axis of the partially completed graph. This was the same for their follow up question, where each group was given a diagram of a different track - step-down track, upwards sloped track and downwards sloped track. See Figure 1.1.1. for reference.

The beaker questions followed the same format. Firstly both groups were presented with a beaker with a cylinder in the middle and were told a constant stream of water was flowing into the beaker. They were given a partially completed graph of water height vs time and asked to complete it. On the diagram of the beaker there were three levels marked, a, b and c, all equally spaced. As before, the partially completed graph contained points a and b on the water level axis. Following the same style of the track questions, both beaker groups were then presented with a diagram of a different beaker configuration. These were referred to as narrowing cone in beaker and half-cylinder in beaker. See Figure 1.1.2. for reference.

Later, 147 students enrolled in a semester 2 module were split into three groups and given questions relating to the resistance along a wire. As the wire questions were administered later in the academic year, preliminary analysis had already been carried out on the track and beaker groups. This led to the formation of some hypotheses which I was able to test by altering the way I presented the wire questions. Rather than providing each group with a unique variation of the experimental setup in the second question, as previously done, they were each given the same experimental setup but the questions were phrased differently. For example, to one group I provided a detailed narrative of how the resistance varied along the wire, to another the wire was rotated 90 degrees to see if orientation had any effect on whether or not they plotted point c. In all wire cases, question one referred to a straight length of even thickness wire, whereas in question two, the wire was of a new, thinner even thickness after the point b. As with the track and beaker questions, the partially completed graph contained points a and b on the distance axis but not c.

With all 8 groups (2 beaker, 3 track, 3 wire), I first checked whether or not students had plotted point c on their position axis. If yes, I then compared |ab| to |bc|. If these distances were the same length I categorised the graph as equal intervals, if not, they were categorised as different intervals. Then their written explanations were analysed to see if they had given a reason for putting it where they had. I discovered that it was possible to group the responses by context as there were no statistically significant differences (as shown by chi-squared testing).

Chi-squared testing was chosen as it tests whether nominal variable are independent of one another, and was thus appropriate in this case. It was also useful as each group had a different sample size, which some statistical tests do not allow (McHugh, 2013).

Two researchers independently coded a sample of the responses and then compared their results to ensure a high level of agreement, before coding the rest of the responses. We felt there was no need to develop a codebook for this part of the study as it was just based on the diagram, and our categories were very self-explanatory.

3.8.3. Categorising graphs - shape

For this section of the study, 323 students were involved (Groups A,B,C,D,E). They were all first year undergraduate students studying non-physics majors, enrolled in the lab based module, Physics for General Science. The students were split into five different sessions according to their timetable, and we employed convenience sampling by giving each of these cohorts a different set of questions. Three groups were given questions relating to a ball rolling along a track, the other two about water flowing into a beaker.

I first categorised students’ responses based on the shape of the graphs that they drew. For this I formed seven different categories - continues slope, parallel slope, steeper line, flatter line, upward curve, downward curve and other, where the terms are relating to the slope of the partially completed graph that was given to the students. See Figure 3.8.1.1. Two researchers independently coded the same random sample and then compared their codes. A high level of agreement was found so I then proceeded to code the rest of the data.

Next, I analysed the students' accompanying written explanations. I formed three broad overarching themes based on what the students had written - overall trend, (initial) rate of change at b, and, interval to be covered. I decided that within each of these categories to class the students' reasoning as a graphical, physical or experimental line of reasoning. When going through the responses I elected to include another category which related to students mentioning force or gravity or friction or constant stream of water. This is referred to as "mechanism".

To code the responses, a codebook was developed iteratively. Two independent researchers coded the same sample of responses and came up with their own criteria for each category. Next, they compared their work and refined the codebook. They coded a new sample using their codebook and again compared their codes. This was repeated until a high level of agreement was obtained. Then the third researcher used the codebook to code a sample and check the usability of the codebook by someone who had not written it. As before, there was a high level of agreement found so I then used the codebook to code all of our data accordingly.

3.8.4. Coding explanations

For the next part of this research, I decided to focus on the structure of the students' written explanations, to see how this affected the graphs that they drew. After a thorough reading of the literature, I decided to use the concept of reasoning chains to analyse the students' responses. I first coded a sample from a beaker group and from a track group independently, as did two other researchers. We then compared our codes and developed a codebook. We repeated this process and edited the codebook in an iterative manner until we agreed that it was objective and unambiguous, and all researchers were confident that it could be applied effectively to the data.

We tried to keep the codebook for the tracks and beakers as analogous as possible. An example of this is using the word "shape" to refer to the shape of the track and the shape of the beaker, as opposed to using both "track" and "beaker". Our codebook consisted of seven elements (eight for the beaker groups) and examples of what words students may have written that we would categorise as one of these elements. The elements were (given conditions), shape, acceleration, speed, graph, time, and gravity. The beaker groups did not feature "gravity", but did require an element "volume" to accurately categorise the responses.

I was very careful to code responses as containing the element "acceleration" only if students made it clear they were thinking of a continual change in speed. The first reason is empirical: an answer like "the velocity changes" could refer to six of the seven graphs shown in Figure 3.8.1.1., so it does not explain why a student would have drawn one of them. The second reason is theoretical: if students are thinking of a graph as emergent (Moore and Thompson, 2015), then they would trace out a curved graph based on the change in speed as time progresses in small increments.

When I initially coded the responses and reduced them to reasoning chains, I dealt with each element as it appeared in the students' responses. Linear reasoning chains were formed of the form "x so y". A simple example would be that if a student wrote "I drew a curve because it accelerates" it would have been coded as "acceleration so graph". After we had each coded a sample in this manner, we discussed our progress and formed a new plan. We decided that in all cases where a student had mentioned something related to the graph, this element should be placed at the end of the reasoning chain. Our reasoning was that students were being asked to explain why they had drawn a graph, therefore there is no logical way in which an element could be a result of the graph, therefore there would be no situation where it would make sense for “so” to follow the element graph. Similarly, we decided that where a student had referred to the fact that the track was frictionless, or the flow of water was constant, this would be coded as the element (given conditions) and placed at the start of the reasoning chain. Our thought process here was that none of the other elements could *cause* these conditions and therefore that element could always be placed at the start of a reasoning chain.

Next, I carried out chi-squared testing to see if it was possible to aggregate the beaker groups and track groups respectively. I did this based on the number of students that had drawn each shape of graph. The results were analysed according to curve/not curve, curve/straight/other and correct curve/other. I discovered (from carrying out chi-squared tests) that the groups could be aggregated by context and that there were no statistically significant differences between the groups when “correct curve/other” was used.

From here I looked at the effect different reasoning chains had on the likelihood of a student drawing the correct graph. The overall percentage of students that had drawn the correct graph was compared to the percentage of students for different reasoning chains to see if any predictive outcomes could be found. Later, I carried out a confounding factor analysis to see if any of the variables were confounding the others.

3.8.5. Confounding factor analysis

For this study we are interested in investigating the effect that mentioning a specific element in a student’s reasoning chain has on their ability to draw the correct graph. In this study the independent variable is categorical, with each category representing a different reasoning chain element. On the other hand, our dependent variable, the shape of the graph, is dichotomous, as the students’ graphs were coded as either correct or incorrect for the purpose of this study. Having one categorical and one dichotomous variable allowed me to use a binary logistics regression. I used a logistics regression as a method of investigating the predictive nature of each of the reasoning chain elements.

By fitting a logistic regression it was possible to check what association, if any, existed between the reasoning chain elements and the shape drawn, i.e. I could check if mentioning a specific keyword made a student more inclined to draw the correct graph. I formed contingency tables for each group including an odds ratio, showing how much more likely a student was to draw the correct graph if they had mentioned a specific element versus if they had not. Next, a table was formed, showcasing the crude odds ratio and the odds ratio after the binary logistic regression model had been applied to the data. Here I was most interested in any element that had a high odds ratio alongside a low significance level as these were the most predictive indicators of all the key elements.

Finally, I took pairs of elements and fitted a univariate logistic regression model to each to see what effect this had on the odds ratio. I decided that should the odds ratio change by more than 10%, this would be considered a significant change, which would suggest that one element was confounding the other. I created a two-way table showing the odds ratios for pairs of elements, whereby the diagonal shows the element paired with itself which naturally is the previously calculated crude odds ratio.

3.8.6. Reliability

When developing the codebooks, the inter-rater reliability was calculated to ensure that a high enough level of agreement was obtained so that we could confidently say that our codes were acceptable.

Later, chi-squared testing was performed on the various groups to ensure that the results could be aggregated together, with $\alpha = 0.05$ as a cut-off point. I discovered that while some of the groups were internally consistent, there was an outlier group which we decided to remove. This is likely due to this cohort of students having less science credits than the others. This was inferred based upon the students' majors, as due to the timetable we could tell which course they were enrolled in. We opted to remove this outlier group, as the intention was to aggregate the track and beaker groups, and therefore removed an outlier group which would skew the results.

After two researchers each coded a sample of the data into equivalent reasoning chains, we calculated Cohen's Kappa to ensure a high level of agreement. Cohen's kappa statistic is often used to check the inter-rater reliability (McHugh, 2012). It was deemed necessary to perform this check, as I wanted to ensure that myself and the other investigator had independently used the codebook in the same manner, thus showing that it was a robust, objective method of categorising the data. This reliability check showed a very high level of agreement and so I continued to code all of the data in this manner.

4. Results

4.1. Results - Intervals and Scaling of Axes

One of the first things that I decided to investigate was how students graphically represent two equal distances shown on a diagram of an experimental setup. The diagram showed either a track, a beaker or a piece of wire, depending on the group. In all cases the diagram contained three points, a, b, and c marked at equal distances. A written piece of text informed the students that they were evenly spaced. In all cases, students were given a partially completed graph where points a and b were drawn on the distance axis. Students were asked to complete the graph and where they plotted the point c was analysed, as well as whether or not they referred to these intervals in their written explanation.

Firstly, I analysed students' graphs to see if they had plotted the point c, and if so, where. Their responses were classed as Equal Interval (|ab|=|bc|), Unequal Interval (|ab|≠|bc|) or No Interval (where they had not included point c). After assessing the responses based on the graphs students had drawn, I then examined their written explanations and categorised them into whether or not they had made reference to the interval.

The results were very interesting as we saw that groups of the same context (i.e. tracks or beakers or wires) could be aggregated together as there were no significant differences (chi-squared testing ensured this). However, across the different contexts there were huge differences in the way that students responded. For example, in Question 1 (where the correct answer was to simply continue the graph in all cases), 94% of students in the beaker groups drew point c on the position axis, however this number dropped to 61% for the wire groups. The results are summarised in the following table. Naturally, when students did not include point c in their graph, they also did not refer to it in their explanations. In fact the only time that I saw a significant number of explanations was within the group of students who correctly drew an equal interval for Question 1.

Table 4.1.1. Student responses for Question 1

	Same Interval			Different Interval	No Interval
	Explanation	*No Explanation*	Total	Total	Total
Beakers (N=137)	*33% (46)*	*56% (77)*	89% (123)	5% (7)	5% (7)
Tracks (N=187)	*10% (19)*	*58% (110)*	68% (129)	13% (25)	17% (33)
Wires (N=145)	*7% (10)*	*47% (68)*	54% (78)	7% (10)	39% (57)

Table 4.1.2. Student responses for Question 2

	Same Interval	Different Interval	No Interval
Beakers (N=137)	67% (92)	15% (21)	17% (24)

Tracks (N=187)	59% (112)	19% (36)	21% (39)
Wires (N=145)	40% (59)	13% (19)	46% (67)

It was found that very few students gave an explanation as to why they had plotted point c where they had on their graphs. In most cases it was an insignificantly small number of students that referred to it in their explanations. The only time a significant number made reference was in question 1 if the students had drawn equal intervals. For example:

> *"The wire is uniform (doesn't change material) and since distance between AB = distance between BC and graph is a straight line through origin from AB it will continue in the same fashion for BC"*
> Group G Student 2

It makes sense that less students provided an explanation in Q2, as if they had already explained it once they may not have thought it necessary to provide another explanation. One student that did explain in Q2 made the following statement:

> *"Point c is again evenly spaced as the points remain the same. I drew a straight line as the water level will still increase at a constant rate. However, I changed the angle of the line as water level will increase a lot slower due to the increased volume to fill."*
> Group B Student 44

It also makes sense why I could not find an explanation as to why they had not plotted point c, as surely if they had not thought to include the point, they had also not thought to write why they had not done so.

Another interesting thing that I found was in the explanations of the few students who had drawn unequal intervals and had explained their reasoning for doing so. These explanations typically stated that they knew it would take longer and they therefore drew an unequal scale on the distance axis to show a lengthening of time. An example of this is:

> *"I did it this way as it will take a shorter time to go from point b to point c than from point a to point b as the track between b and c has a steeper gradient so it will take shorter"*
> Group C Student 11

After the initial round of questions were given to the track and beaker groups I saw that students in the track groups were less inclined to plot point c on the position axis. I hypothesised that a,b,c being vertical on the beaker made it easier for students to translate this to the vertical position axis than in the track questions where a,b,c are horizontal on the diagram. To see what effect orientation had on whether or not students plotted point c, the wire question was asked with the same phrasing but with the wire in both a vertical and a horizontal orientation. However, surprisingly, there were no statistically significant differences between the wire groups and thus I was able to aggregate them as I had done with the tracks and beakers. This led to a new hypothesis that context plays a much larger role than orientation on whether or not students plot the point c.

4.2. Results - Initial Coding of Shapes

For this part of the research I focused on the student responses to Q2, where the experimental set up had changed and required them to alter the graph rather than just continue the straight line.

Initially, the five original groups were coded based on the shape of graphs the students drew. I formed 7 categories that were mutually exclusive and collectively exhaustive. The categories were as follows: *continues slope*, *parallel slope*, *steeper line*, *flatter line*, *upward curve*, *downward curve*, and *other*. These categories are all self-explanatory (where each category title relates the part of the graph that students drew to the supplied section) apart from parallel slope which may require some further explanation. This type of graph only appeared in the group of students that were given a step-down track. Essentially, they drew a small kink in the graph and then continued with the same slope as had been given in the partially completed graph. The accompanying explanations typically stated that it would speed up as it went down the ramp then continue at a constant speed.

Our results were very surprising. We saw that in three of the groups, where the correct answer would have been a curve, a very large proportion of students were inclined to draw straight lines. The results are shown in Table 4.2.1.

Table 4.2.1. Shapes students drew for Question 2

	step-down track (n=59)	downward sloped track (n=59)	upward sloped track (n=68)	half cylinder in beaker (n=74)	cone in beaker (n=63)
continues slope	14% (8)	14% (8)	9% (6)	9% (7)	6% (4)
parallel slope	12% (7)	0% (0)	0% (0)	0% (0)	0% (0)
steeper line	**58% (34)**	58% (34)	1% (1)	3% (2)	10% (6)
flatter line	7% (4)	2% (1)	34% (23)	**74% (55)**	43% (27)
upward curve	5% (3)	**25% (15)**	1% (1)	0% (0)	6% (4)
downward curve	0% (0)	0% (0)	**38% (26)**	0% (0)	**33% (21)**
other	5% (3)	2% (1)	16% (11)	14% (10)	2% (1)

In each column the correct answer is in bold. After seeing the large percentage of students that drew a straight line where a curve would be more appropriate, I began to investigate their written explanations. I wanted to see if the context of the question affected the language that students used to explain their graphs. We formed a codebook iteratively and would repeatedly code sections individually before comparing and conferring with each other to adjust the wording.

We found that the best way to format the codebook was as a series of questions. For example, under the category "(initial) rate of change at b - graphical" we had the question: *Do students compare their line to the initial line by using words such as: it got steeper/flatter/shallower, it curved up/down?* With each response, I went through every category in the codebook and coded a 1 if the answer was yes, and a 0 if the answer was no. The results from this analysis are shown in the table below.

Table 4.2.2. Arguments students used for Question 2

group %	overall trend			(initial) rate of change at b			interval to be covered			mechanism
	G	P	E	G	P	E	G	P	E	
step-down track	7	27	3	15	100	93	0	31	3	22
downward sloped track	10	10	0	18	87	87	0	39	0	23
upward sloped track	20	20	0	10	81	90	0	33	7	33
half-cylinder in beaker	9	14	3	20	27	72	4	69	77	24
cone in beaker	19	17	23	9	17	61	6	70	67	17

This analysis showed us some very interesting differences between the tracks and the beakers. As evident in the table, students presented with track questions tended to write more about the (initial) rate of change (both physical and experimental), whereas students given beaker questions tended to focus more on the interval to be covered (both physical and experimental). It was found that a similarly low percentage of students referred to the overall trend in any of the tracks or beaker groups.

I have interpreted these findings, in relation to the large number of students that drew straight lines instead of curves, as follows: students appear to focus on what happens at b or at c but not what happens in between. The “overall trend” category relates to the whole process, whereas (initial) rate of change is directly relating to point b. Similarly, “interval to be covered” deals with total distance or time and is more closely related to point c than to a segment. I think that by focusing on individual points along the track or up the beaker, students are missing the fact that the rate changes throughout the process and are therefore coming to the incorrect conclusion that a straight line with a different slope is the correct solution, where in reality, a curve is more appropriate as it changes throughout.

4.3. Results - Final Coding of Shapes

For this part of the study I studied five of the eight track groups and four of the seven beaker groups. Chi-squared testing was used to ensure that these groups were internally consistent with each other and could be aggregated into tracks and beakers. This was why I felt it necessary to exclude some of the other groups as the chi-squared test showed they were too different, likely due to the cohort of students that were in that group. Also excluded were the groups where they had been asked to explain what happens prior to drawing the graph, and to then also explain their graph, as we found it hard to code their reasoning chains in this case.

It was decided that for this section of the study, I would dichotomously categorise the graphs as either correct or incorrect. This enabled me to then see what effect different reasoning chains had on students' performance.

I looked at what effect each element had on whether or not a student drew the correct graph. This was done by getting the overall percentage of correct answers and comparing it against students that had, and those that hadn't, used a specific element in their reasoning chain. Here, chi-square testing was again carried out, and then the individual groups were aggregated into tracks and beakers. I performed a logistic regression on the data and calculated the odds ratio of each element. Our most significant findings were that mentioning “acceleration” and “graph” greatly increased one's likelihood of drawing the correct graph, whilst mentioning friction or constant flow made a student far less likely to do so. I theorise that this is largely due to the fact that students who mentioned friction/constant flow were engaged in static thinking and were more likely to draw a straight line graph, whilst those that mentioned acceleration were thinking more emergently and drew a curve.

Next, I carried out confounding factor analysis to account for any effect that confounding variables may have had. This is a standard procedure to ensure that the presence/absence of one variable does not mask the effect of another variable. Tables 4.3.1. and 4.3.2., for the tracks and beakers respectively, show the results of what happened to the odds ratio for each pair of elements, to show what effect confounding factors may be playing. The tables show if the variables in the left column have a confounding effect on those in the top row. For example, in the case of tracks, mentioning friction confounds gravity by 2.48 times.

Table 4.3.1. Odds ratios of the track groups after confounding factor analysis. Entries on the diagonal show crude odds ratios. The table shows how the odds ratio for the variable on the top row changes when controlling for the variable in the corresponding row. Odd ratios that change by more than 10% are indicated in bold.

track	**friction**	**slope**	**gravity**	**acceleration**	**speed**	**time**	**graph**
friction	0.24	0.58	**2.48**	2.49	0.88	0.74	2.32
slope	0.26	0.54	**2.36**	2.35	0.94	0.72	2.24
gravity	**0.21**	0.50	2.07	2.42	0.85	0.76	2.61
acceleration	0.25	**0.61**	1.87	2.50	**1.21**	0.76	2.31
speed	0.24	0.54	2.09	2.62	0.86	0.73	2.40
time	0.24	0.52	2.07	2.50	0.81	0.76	2.41
graph	0.25	**0.60**	**2.49**	2.42	0.86	0.74	2.40

Table 4.3.2. Odds ratios of the beaker groups after confounding factor analysis. Entries on the diagonal show crude odds ratios. The table shows how the odds ratio for the variable on the top row changes when controlling for the variable in the corresponding row. Odd ratios that change by more than 10% are indicated in bold.

beaker	**flow**	**shape**	**volume**	**acceleration**	**speed**	**time**	**graph**
flow	0.47	1.08	1.10	4.32	0.68	0.75	2.20
shape	0.47	1.04	1.04	4.79	0.70	0.70	2.31
volume	0.46	1.03	1.05	4.90	0.70	0.68	2.38
acceleration	**0.63**	**1.37**	**1.45**	4.47	**0.79**	**0.83**	**1.81**
speed	0.48	1.01	1.01	4.40	0.70	**0.60**	2.46
time	0.51	1.12	**0.51**	4.36	**0.59**	0.71	2.21
graph	**0.53**	**1.15**	**1.20**	**4.01**	**0.60**	0.75	2.27

Tables 4.3.1 and 4.3.2 show that in the beaker groups, mentioning acceleration confounds every other variable, however in the track groups it only confounds slope and speed. Similarly, in the beaker groups, “graph” confounds 5 of the other 6 elements (excluding time), unlike in the track groups where it only confounds slope and gravity.

The most dramatic confounding effect found was that mentioning time confounds mentioning volume by 50% in a negative manner. My best theory as to why mentioning time has such a negative impact on volume, is that students are thinking of the total time and total volume required and that they form an endpoint of their graph and then joining the dots to reach that endpoint as opposed to considering the process and overall experiment. This would be an example of static graphical reasoning (Moore and Thompson, 2015), where students fit static images of graphs to reflect the features they considered.

The most surprising thing learned in this part of the project was how students are much more likely to draw the correct graph if they explicitly refer to the graph in their explanation. This suggests that merely focusing on the graph increases one’s performance.

5. Conclusion

5.1. Summary of Findings

As illustrated throughout this thesis, my research shows what has been known by practitioners for years, that students find graphs difficult to understand. My project differs from the existing literature as it focuses solely on students drawing qualitative graphs for a given theoretical experiment. It was seen throughout the three projects that students struggle greatly when asked to construct a qualitative graph, and that the context of the question is a huge predictor of how difficult they will find it. This work has led to a refereed publication (Condon *et al*, 2024) and a second paper has been submitted to Physical Review (Condon *et al*, submitted)

It was very surprising to see that the wording of the question had a very small effect on whether or not the students drew the correct corresponding graph. I had hypothesised that if students were presented with a more detailed narrative, explaining what happened throughout the theoretical experiment, that this would result in a much higher percentage of students drawing the correct graph, however, this proved not to be the case. I interpret this as a validation of the normal form of the question, in that it provided students with all the clues they needed to visualise the process, but that this visualisation did not cue them to construct or choose a curved graph. In terms of resource theory (Hammer *et al*, 2005), this still leaves open the question if these students do not possess or cannot coordinate the resources needed to do this, or if the questions somehow do not trigger this line of thought.

I was also fascinated by how large an indicator explicitly mentioning the graph was on whether or not students would draw the correct graph. This highly positive indicator suggests that when students make an explicit reference to their graph, they are far more likely to draw it correctly. This knowledge is of huge importance to educators, who can perhaps alter their teaching styles in an attempt to further students' understanding. Having a better glimpse into students' thought processes when completing graphing tasks will allow teachers to guide their students more appropriately.

In relation to my research questions outlined in Section 1.3., I can draw the following conclusions. Firstly, in relation to representing intervals, I saw that context played a huge role in whether or not students drew an equal interview on their graph, as was appropriate to do so. It appears that the more abstract the scenario, the less likely students were to plot the point c on their graph, and thus over two fifths of students did not draw point c in the wire groups. In the beaker groups however, 89% of students drew equal intervals in Question 1. This effect of context is also relevant to RQ2, whereby the types of arguments given by the students were under consideration. Here I saw that in the track groups, students tended to provide both physical and experimental arguments relating to the (initial) rate of change. This was in strong contrast with students in the beaker groups who instead focused on the interval to be covered.

Finally, to address RQ3 and RQ4 I identified the equivalent reasoning chains students formed when completing these tasks as a fruitful way to code the students' open-response explanations. It was found that the students’ arguments could be captured as a combination of seven elements without losing the essence of their explanations. This showed us that regardless of how “correct” their responses were, the students all used the same key terms to describe the situation. Whilst the tracks and beakers required a different list of elements, four of the seven key words were the same indicating that students used similar arguments irrespective of context. Students whose reasoning included “acceleration” and “gravity” were far more likely to come up with a correct graph, whilst mentioning “time”, “frictionless” and “constant flow rate” had a negative impact on performance. My belief is that the students who mentioned “frictionless” or “constant flow rate” reached the conclusion that because friction wasn’t slowing the ball / the flow rate wasn’t changing, that nothing else would cause the graph to change either. As for those who made explicit reference to “time”, I believe they were more focused on the total time taken and thus plotted a point which showed a greater/lesser time interval which they then connected to the partially completed graph without considering how the motion changed during that interval.

Surprisingly, students who mentioned “graph” were more likely to draw a correct graph than those who didn’t. It seems unusual that simply mentioning the word graph has such a positive effect on students' performance, which of course begs the question, is this a cause or an effect? From the data gathered in this study, I do not believe it is possible to claim whether mentioning “graph” causes students to draw the correct graph, or vice versa. It is clear that there is correlation between the two, however it would be incorrect for me to claim that there is causation, without further evidence.

5.2. Future Studies

One particular area of interest that was unfortunately beyond the scope of this project, was whether or not the order in which students mentioned the elements in their reasoning chains has any effect on the confounding effect. I believe this would require an extensive amount of research and that a larger number of participants would be necessary, as although many students used the same reasoning in their answer, no two answers were precisely the same. Of course by reducing their answer down to the key elements, as outlined above, this would reduce the number of unique responses, but, nonetheless, if order was now taken into consideration then a larger sample size would be necessary for any meaningful statistical analysis to be carried out.

Another possibility would be to approach it from a more qualitative point of view, perhaps by the use of interviews. As previously mentioned, I attempted to gather participants to be interviewed, but only found two students that were willing. I would love to see more interviews be carried out in this area. I think that it is possible that students tried to formalise their answers or make themselves sound “smart” as it was part of an assessment for their course. Interviews would reduce this and one would get a glimpse into their initial thoughts, as opposed to what they choose to write down during an exam.

Whilst my hypothesis that the orientation of the beaker versus that of the track affected whether or not students would plot the point c was not supported within the wire questions, I think there is more scope to investigate this further. It has been shown that the context affects the likelihood of students plotting point c, but I would love to see more contexts investigated, and also for the idea of orientation to be studied more. Obviously, it is not possible to rotate either the beaker or track questions by 90 degrees to test the effects of orientation, and so one would have to form a new genre of question.

A final possibility of which future studies could examine would be to administer a set of questions at the start of a module and then again at the end of the module to see if the students' approaches and understanding of graphs has changed as a result of the intervention of some tuition on the subject. Whilst I administered questions at different times throughout the module, they were in different contexts and thus it is not possible to ascertain whether or not the students' understanding changed.

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Appendix Table of Contents

Appendix A - Codebook

category		**criteria/questions**
overall trend	graphical	Do students mention the overall shape of the graph (straight or curved)? Do not code here for e.g. a kink at point b.
	physical	Do students say something about the speed being constant or that it speeds up or slows down throughout the process? Do not code if there is only a comparison to the speed on a-b.
	experimental	Do students say that after the step-down track, the track from b-c is flat/horizontal or sloped? Do students say that the cone gets narrower throughout b-c so that the volume is reducing as the water rises? Do students say that there is a new constant volume after the half cylinder?
(initial) rate of change at b	graphical	Do students compare their line to the initial line by using words such as: it got steeper / flatter / shallower, it curved up/down?
	physical	Do students describe the motion of the ball/rate of change of the water level by using words such as gets faster/slower, speeds up/slows down? Looking for a distinction between a-b and b-c as opposed to the motion changing throughout b-c
	experimental	Do students comment on the change in the setup such as: there is a ramp / there is no cylinder in b-c / the track slopes?
interval to be covered	graphical	Do students discuss the length of the line? Do students discuss the interval between a-b and b-c in terms of the axes?
	physical	Do students discuss the overall time taken or distance travelled by using words such as “it took longer” / “more distance covered in less time”/ “it takes more time”?
	experimental	Do students discuss the total volume of water needed or use words such as “to fill the beaker”? Do students discuss the length of the track (which they may call “the distance” but not “the distance travelled”) or height of the beaker?
mechanism		Do students refer to gravity / force / friction / constant stream of water?

Appendix B - Plain Language Statement

PLAIN LANGUAGE STATEMENT YEAR 1 STUDENTS

Dear student,

My name is Orlaith Condon (orlaith.condon3@mail.dcu.ie), and I am a researcher at the School of Physical Sciences and the Centre for the Advancement of STEM Teaching and Learning (CASTeL) here at Dublin City University.

As part of my research, which is being funded by the School of Physical Sciences, I am investigating how first-year students construct graphs related to physics. The Data Controller of this research is DCU, and the DCU Data Protection Officer is Mr. Martin Ward (data.protection@dcu.ie Ph.: 7005118 / 7008257). If you are unhappy with my research you may contact Mr. Ward, or you may lodge a complaint with the Irish Data Protection Commission.

My study will not require anything of you that you would not normally do. I will look at students' anonymised responses to questions about graphs in the normal assessments of this module. I will never know who wrote or drew what, I will only ever see work from students who agree to participate in this study with their names removed.

I will also ask some of you to participate in an interview to explore why you drew graphs the way you did. If you agree to take part, the interview will be arranged for a time that suits you. All information gathered during this study will be kept confidential and non-attributable. If you take part in an interview, you will be given a code name so that your identity will not be known. At all times your confidentiality will be protected within the limits of the law. Confidentiality of information can only be protected within the limitations of the law - i.e., it is possible for data to be subject to subpoena, freedom of information claim or mandated reporting by some professions. I will keep the data safely stored at all times, and I will destroy all information related to the study three years after its completion.

There are no risks involved in this research project. In fact, the research will help us understand how we can improve how lecturers teach and students learn graphing. All data collected and stored during this study will be GDPR compliant. If you wish to view your personal data at any stage, or you wish for your data to be removed from the study, you may contact me, and I will make the necessary arrangements.

It is completely your choice whether to take part in this research project or not. If you are willing to participate in this research, please indicate that by signing the consent form attached. You do not have to take part if you do not wish to. If you decide during the research that you do not want to take part anymore, all you have to do is tell me. There are no penalties for pulling out at any stage. If you decide not to participate there will be no repercussions and your relationship with DCU will not be affected now or in the future.

If you have any questions or require further clarification, please feel free to contact me at the below address. Thank you in advance for your participation.

Orlaith Condon
orlaith.condon3@mail.dcu.ie

If participants have concerns about this study and wish to contact an independent person, please contact:

The Secretary, Dublin City University Research Ethics Committee, c/o Research and Innovation Support, Dublin City University, Dublin 9. Tel 01-7008000, e-mail rec@dcu.ie

Appendix C - Informed Consent Form

INFORMED CONSENT FORM FOR YEAR 1 STUDENTS

Dear student,

This research project investigates how students draw graphs related to physics. If you agree to participate in this research, I may use some of your work in anonymised form. You may also be asked to take part in an interview about drawing graphs in physics.

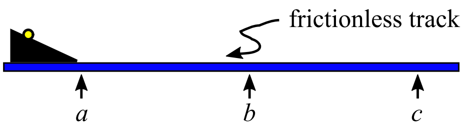
Please complete the following circling Yes or No for each question:

I have read or have read to me the Plain Language Statement	Yes	No
I understand what the project is about	Yes	No
I understand the information provided in relation to data protection	Yes	No
I have had an opportunity to ask questions and discuss this study	Yes	No
I have received satisfactory answers to all my questions	Yes	No
I know that my real name will not be used	Yes	No
I know that I can drop out of the study if I want to	Yes	No
I want to take part in this study	Yes	No
I know that I may be invited to take part in an audiotaped interview but I do not have to participate if I don't want to	Yes	No

Name: ___________________________

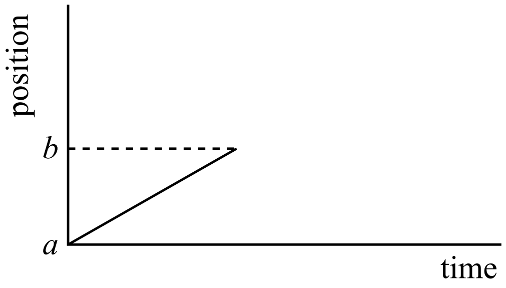
Date: ___________________________

2. A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp.



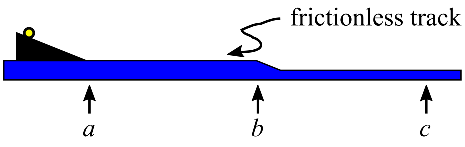
After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

a. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

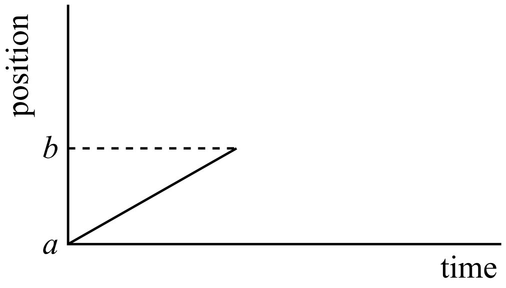


b. Explain why you drew the graph the way you did.

She then repeats the experiment on the track shown at right. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.

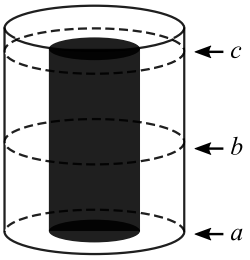


c. Complete the graph so that it represents the motion of the ball between points *a* and *c*.



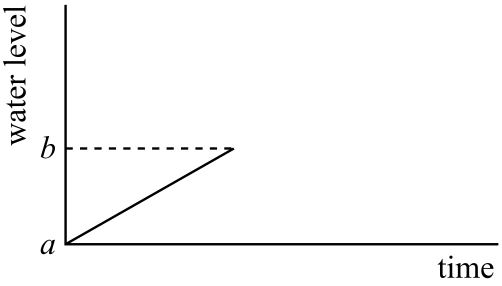
d. Explain why you drew the graph the way you did.

2. A student fills a beaker using a constant stream of water. There is a solid cylinder inside the beaker. The student has marked three levels (*a*, *b*, and *c*) evenly spaced along the beaker. She starts her stopwatch when the water reaches point *a*, at the bottom of the beaker.



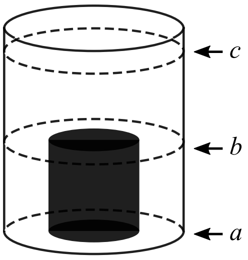
After she has completed her measurements, she draws a graph showing how the water level changes with time. The part of her graph that represents the change between levels *a* and *b* is shown.

a. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.

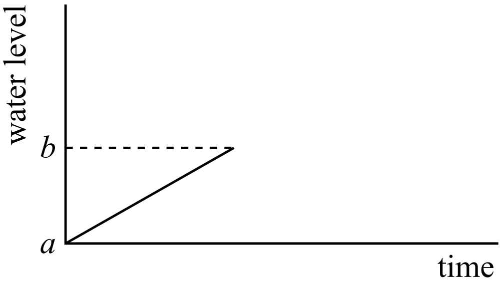


b. Explain why you drew the graph the way you did.

She then repeats the experiment but replaces the cylinder with the shorter cylinder as shown at right. Again the part of her graph that represents how the water level changes with time between levels *a* and *b* is shown.

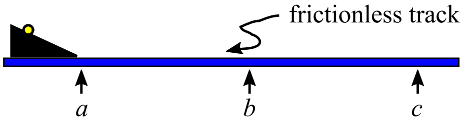


c. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.



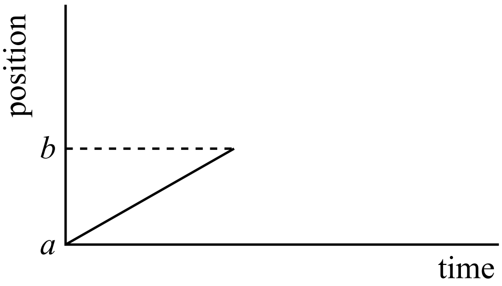
d. Explain why you drew the graph the way you did.

2. A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp.



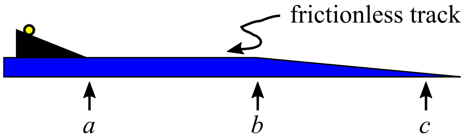
After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

a. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

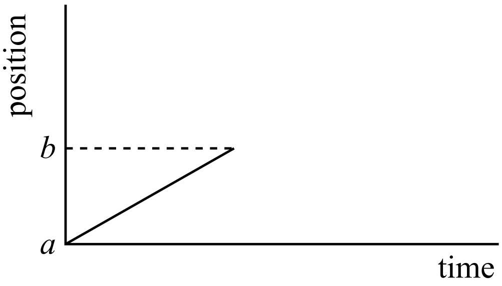


b. Explain why you drew the graph the way you did.

She then repeats the experiment on the track shown at right. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.

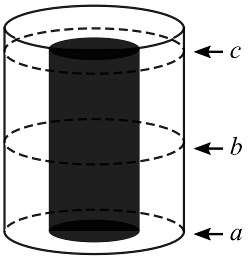


c. Complete the graph so that it represents the motion of the ball between points *a* and *c*.



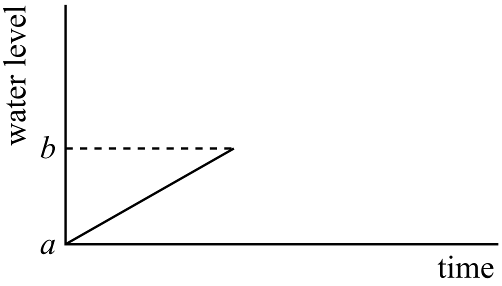
d. Explain why you drew the graph the way you did.

2. A student fills a beaker using a constant stream of water. There is a solid cylinder inside the beaker. The student has marked three levels (*a*, *b*, and *c*) evenly spaced along the beaker. She starts her stopwatch when the water reaches point *a*, at the bottom of the beaker.



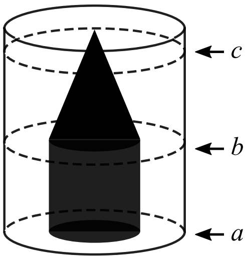
After she has completed her measurements, she draws a graph showing how the water level changes with time. The part of her graph that represents the change between levels *a* and *b* is shown.

a. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.

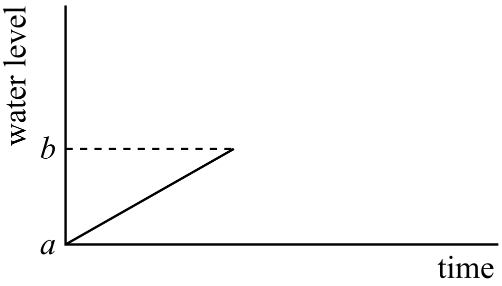


b. Explain why you drew the graph the way you did.

She then repeats the experiment but replaces the cylinder with the shape shown at right. Again the part of her graph that represents how the water level changes with time between levels *a* and *b* is shown.

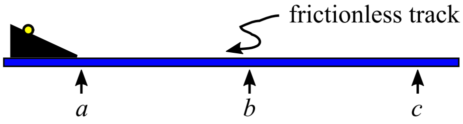


c. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.



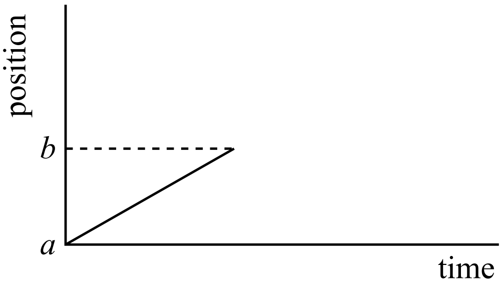
d. Explain why you drew the graph the way you did.

2. A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp.



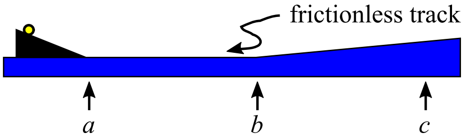
After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

a. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

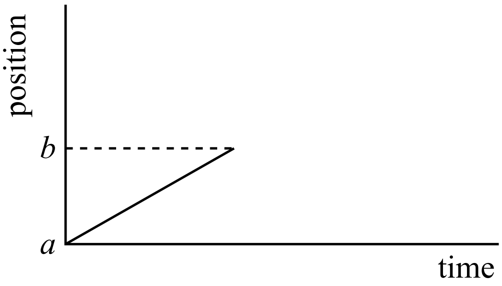


b. Explain why you drew the graph the way you did.

She then repeats the experiment on the track shown at right. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.

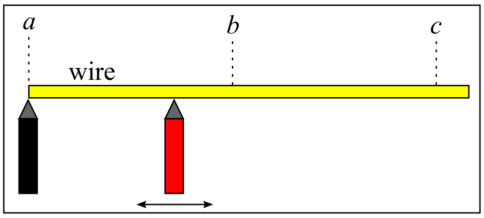


c. Complete the graph so that it represents the motion of the ball between points *a* and *c*.



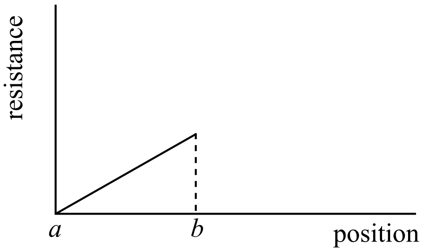
d. Explain why you drew the graph the way you did.

2. A student measures the resistance of a wire between two points. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the wire. She keeps the black lead at one end of the wire, and moves the red lead between points *a* and *c*, measuring the resistance of the part of the wire that is between the two leads as she goes along.



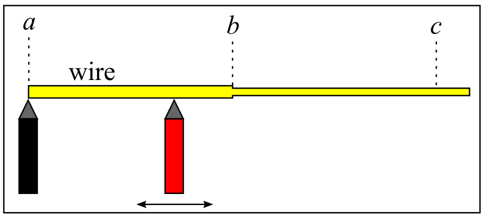
After she has completed her measurements, she draws a graph showing how the resistance changes with the position of the red lead. The part of her graph that represents the change between points *a* and *b* is shown.

a. Complete the graph so that it represents how the resistance changes with the position of the red lead between points *a* and *c*.

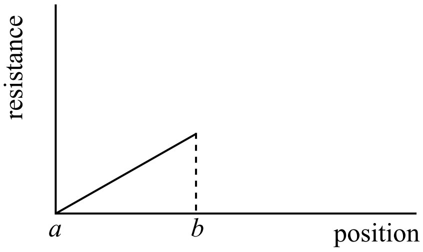


b. Explain why you drew the graph the way you did.

She then repeats the experiment but replaces the wire with a wire that is thinner to the right of point *b*, as shown at right. Again the part of her graph that represents the change of resistance as the position of the red lead changes between points *a* and *b* is shown.



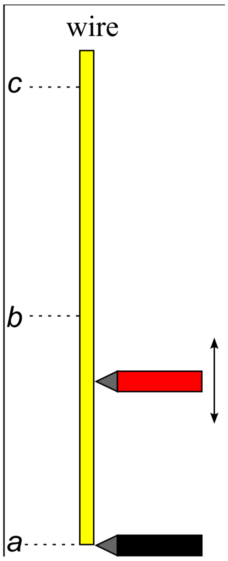
c. Complete the graph so that it represents how the resistance changes with the position of the red lead between points *a* and *c*.



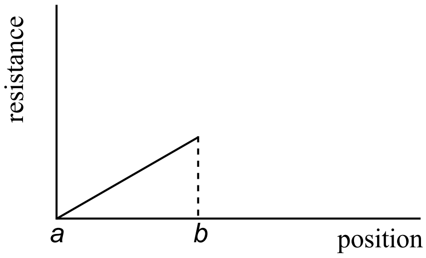
d. Explain why you drew the graph the way you did.

2. A student measures the resistance of a wire between two points. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the wire. She keeps the black lead at one end of the wire, and moves the red lead between points *a* and *c*, measuring the resistance of the part of the wire that is between the two leads as she goes along.

   After she has completed her measurements, she draws a graph showing how the resistance changes with the position of the red lead. The part of her graph that represents the change between points *a* and *b* is shown.

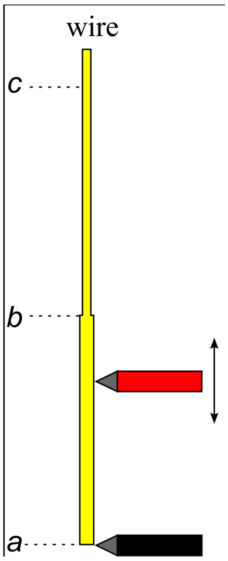


   a. Complete the graph so that it represents how the resistance changes with the position of the red lead between points *a* and *c*.

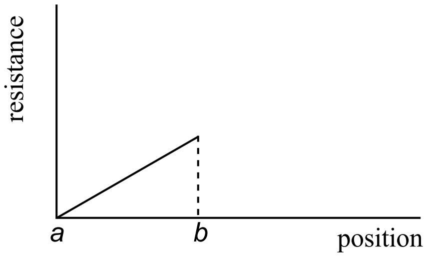


   b. Explain why you drew the graph the way you did.

   She then repeats the experiment but replaces the wire with a wire that is thinner to the right of point *b*, as shown at right. Again the part of her graph that represents the change of resistance as the position of the red lead changes between points *a* and *b* is shown.

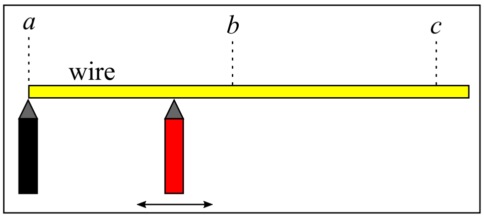


   c. Complete the graph so that it represents how the resistance changes with the position of the red lead between points *a* and *c*.



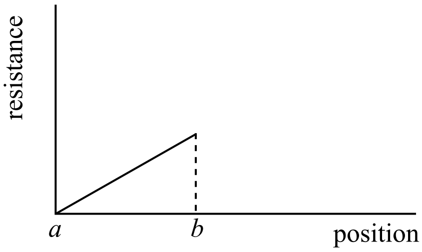
   d. Explain why you drew the graph the way you did.

2. A student measures the resistance of a wire between two points. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the wire. She keeps the black lead at one end of the wire, and moves the red lead between points *a* and *c*, measuring the resistance of the part of the wire that is between the two leads as she goes along. She finds that for every cm the red lead moves to the right, the resistance increases by the same amount all the time.



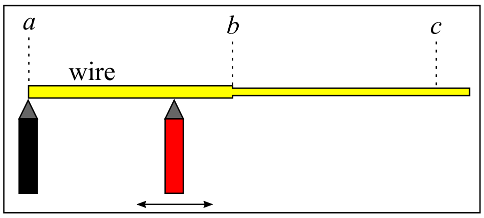
After she has completed her measurements, she draws a graph showing how the resistance changes with the position of the red lead. The part of her graph that represents the change between points *a* and *b* is shown.

a. Complete the graph so that it represents how the resistance changes with the position of the red lead between points *a* and *c*.

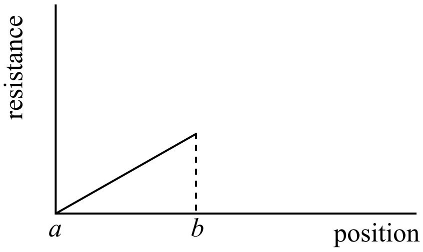


b. Explain why you drew the graph the way you did.

She then repeats the experiment but replaces the wire with a wire that is thinner to the right of point *b*, as shown at right. She finds that between points *b* and *c* the resistance increases by a constant amount for every cm, but that this constant amount is greater than it was between *a* and *b*. Again the part of her graph that represents the change of resistance as the position of the red lead changes between points *a* and *b* is shown.

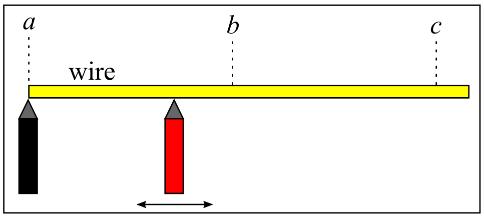


c. Complete the graph so that it represents how the resistance changes with the position of the red lead between points *a* and *c*.



d. Explain why you drew the graph the way you did.

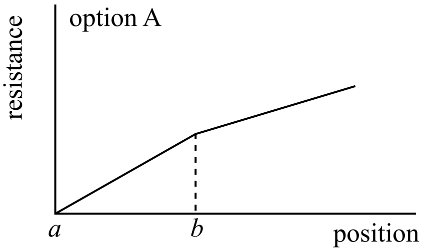
2. A student measures the resistance of a wire between two points. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the wire. She keeps the black lead at one end of the wire, and moves the red lead between points *a* and *c*, measuring the resistance of the part of the wire that is between the two leads as she goes along.

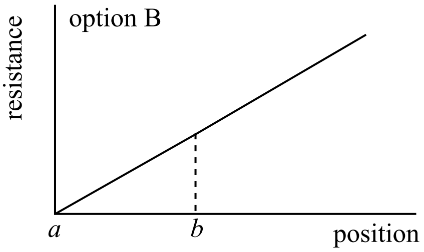


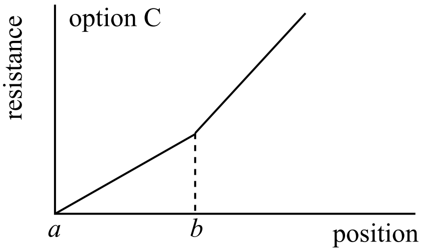
After she has completed her measurements, she draws a graph showing how the resistance changes with the position of the red lead.

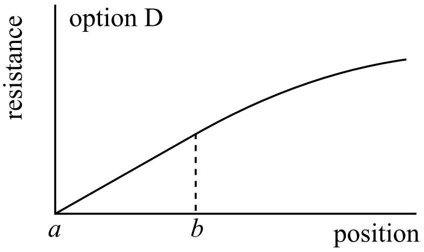
a. Which of the graphs A–E best represents how the resistance changes with the position of the red lead between points *a* and *c*?

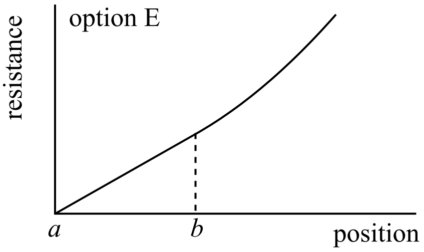
b. Explain how you made your choice and how you ruled out the other options.



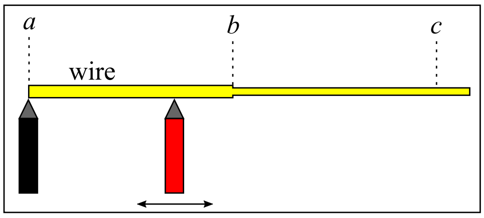








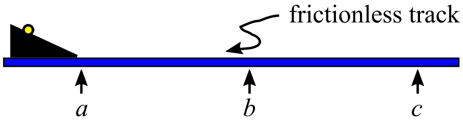
She then repeats the experiment but replaces the wire with a wire that is thinner to the right of point *b*, as shown below.



c. Which of the graphs A–E best represents how the resistance changes with the position of the red lead between points *a* and *c*?

d. Explain how you made your choice and how you ruled out the other options.

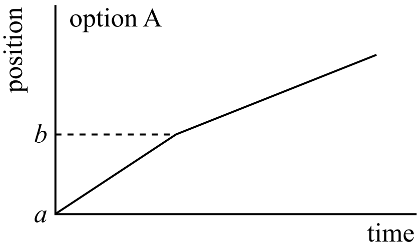
2. A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp.

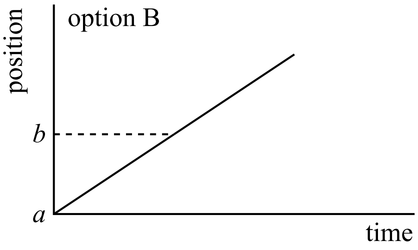


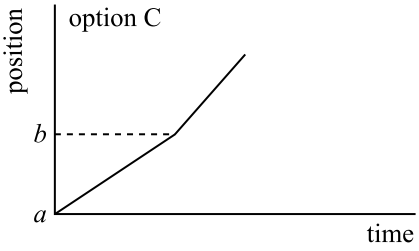
After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

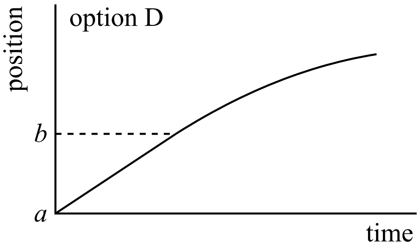
a. Which of the graphs A–E best represents how the position of the ball changes with time between points *a* and *c*?

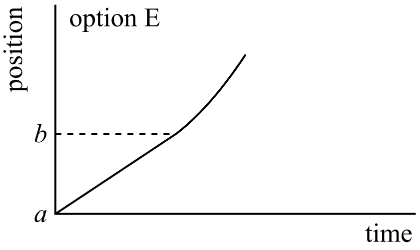
b. Explain how you made your choice and how you ruled out the other options.



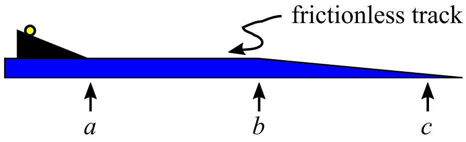








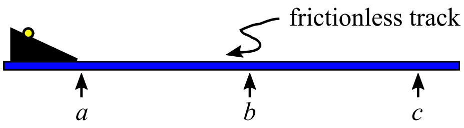
She then repeats the experiment on the track shown at right. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.



c. Which of the graphs A–E best represents how the position of the ball changes with time between points *a* and *c*?

d. Explain how you made your choice and how you ruled out the other options.

2. A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp.

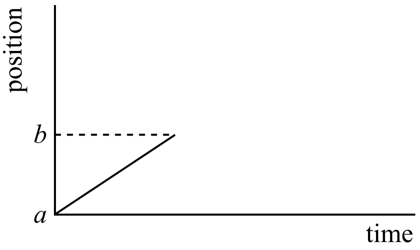


After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

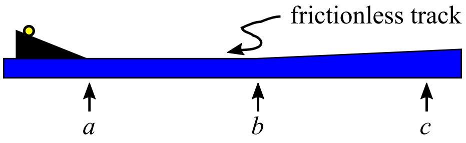
a. Describe the motion of the ball.

b. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

c. Explain why you drew the graph the way you did.



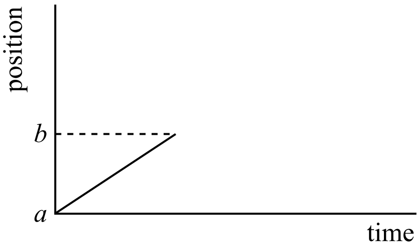
She then repeats the experiment on the track shown at right. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.



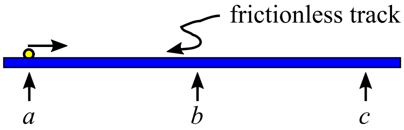
d. Describe the motion of the ball.

e. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

f. Explain why you drew the graph the way you did.

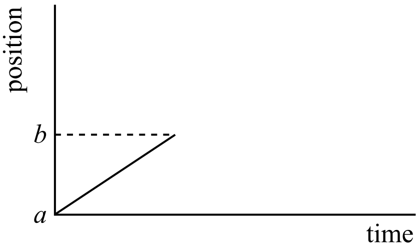


2. A student rolls a ball along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp.



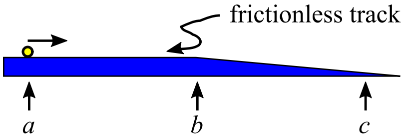
After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

a. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

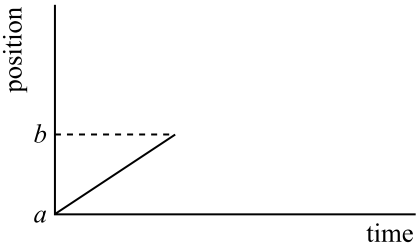


b. Explain why you drew the graph the way you did.

She then repeats the experiment on the track shown at right. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.

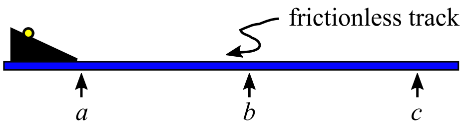


c. Complete the graph so that it represents the motion of the ball between points *a* and *c*.



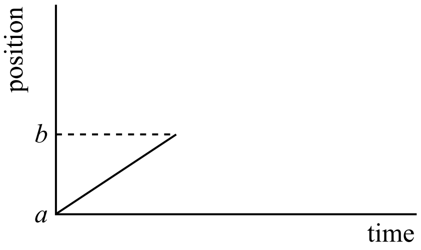
d. Explain why you drew the graph the way you did.

2. A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp. She finds that for every millisecond the ball moves to the right, the position along the track increases by the same amount all the time.



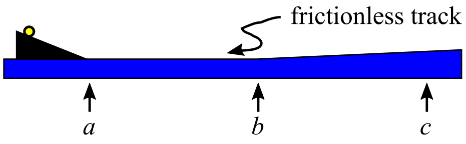
After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

a. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

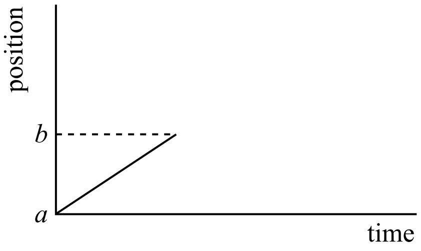


b. Explain why you drew the graph the way you did.

She then repeats the experiment on the track shown at right. She finds that between points *b* and *c* the position increases by a continually creasing amount for every millisecond. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.

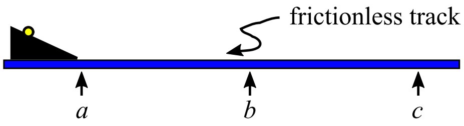


c. Complete the graph so that it represents the motion of the ball between points *a* and *c*.



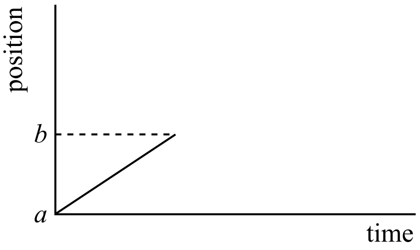
d. Explain why you drew the graph the way you did.

2. A student releases a ball from rest at the top of a ramp. The ball then rolls along the frictionless track shown at the right. The student has marked three points (*a*, *b*, and *c*) evenly spaced along the track. She starts her stopwatch when the ball reaches point *a*, at the bottom of the ramp. She finds that for every millisecond the ball moves to the right, the position along the track increases by the same amount all the time.



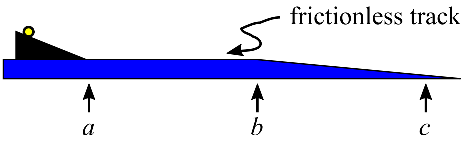
After she has completed her measurements, she draws a position-time graph. The part of her graph that represents the motion of the ball between points *a* and *b* is shown.

a. Complete the graph so that it represents the motion of the ball between points *a* and *c*.

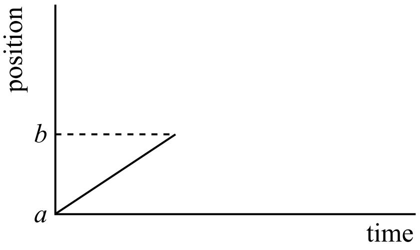


b. Explain why you drew the graph the way you did.

She then repeats the experiment on the track shown at right. She finds that between points *b* and *c* the position increases by a continually increasing amount for every millisecond. Again the part of her graph that represents the motion of the ball between points *a* and *b* is shown.

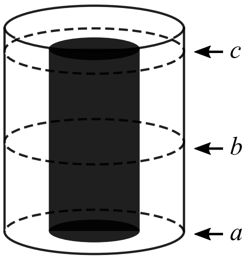


c. Complete the graph so that it represents the motion of the ball between points *a* and *c*.



d. Explain why you drew the graph the way you did.

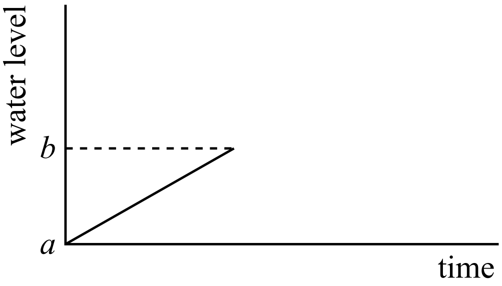
2. A student fills a beaker using a constant stream of water. There is a solid cylinder inside the beaker. The student has marked three levels (*a*, *b*, and *c*) evenly spaced along the beaker. She starts her stopwatch when the water reaches point *a*, at the bottom of the beaker. She finds that for every millisecond that passes, the water level increases by the same amount all the time.



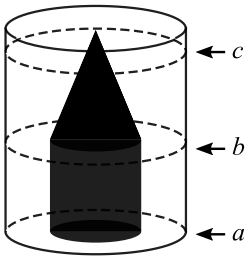
After she has completed her measurements, she draws a graph showing how the water level changes with time. The part of her graph that represents the change between levels *a* and *b* is shown.

a. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.

b. Explain why you drew the graph the way you did.

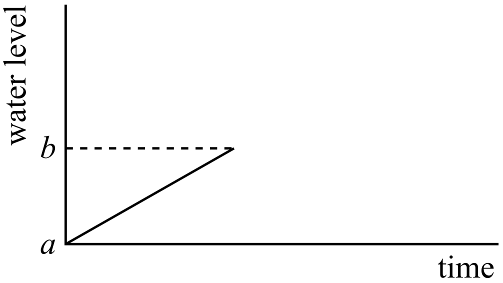


She then repeats the experiment but replaces the cylinder with the shape shown at right. She finds that between points *b* and *c* the water level increases by a smaller amount every millisecond. Again, the part of her graph that represents how the water level changes with time between levels *a* and *b* is shown.

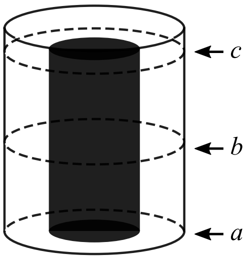


c. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.

d. Explain why you drew the graph the way you did.



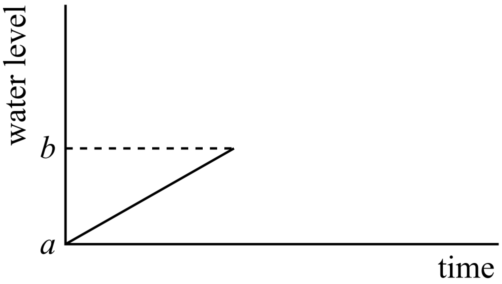
2. A student fills a beaker using a constant stream of water. There is a solid cylinder inside the beaker. The student has marked three levels (*a*, *b*, and *c*) evenly spaced along the beaker. She starts her stopwatch when the water reaches point *a*, at the bottom of the beaker. She finds that for every millisecond that passes, the water level increases by the same amount all the time.



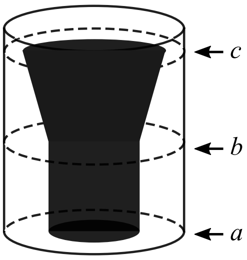
After she has completed her measurements, she draws a graph showing how the water level changes with time. The part of her graph that represents the change between levels *a* and *b* is shown.

a. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.

b. Explain why you drew the graph the way you did.

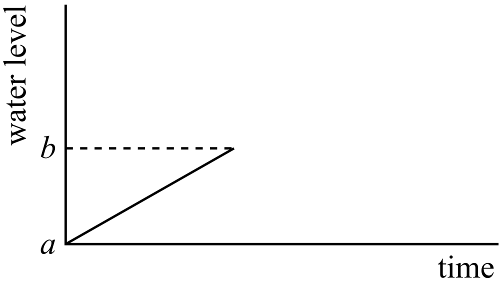


She then repeats the experiment but replaces the cylinder with the shape shown at right. She finds that between points *b* and *c* the water level increases by a greater amount every millisecond. Again, the part of her graph that represents how the water level changes with time between levels *a* and *b* is shown.

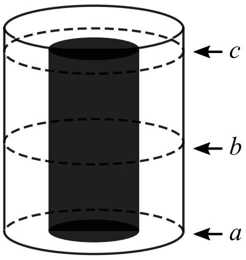


c. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.

d. Explain why you drew the graph the way you did.

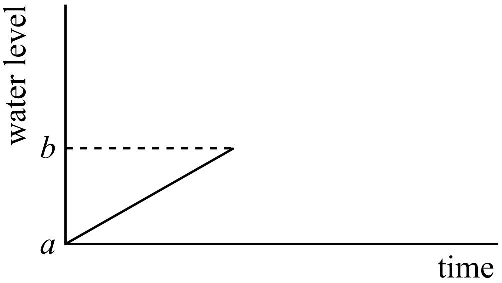


2. A student fills a beaker using a constant stream of water. There is a solid cylinder inside the beaker. The student has marked three levels (*a*, *b*, and *c*) evenly spaced along the beaker. She starts her stopwatch when the water reaches point *a*, at the bottom of the beaker.



After she has completed her measurements, she draws a graph showing how the water level changes with time. The part of her graph that represents the change between levels *a* and *b* is shown.

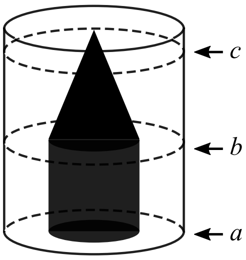
a. Describe how the water level changes over time.



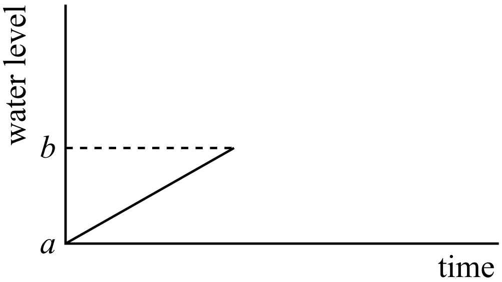
b. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.

c. Explain why you drew the graph the way you did.

She then repeats the experiment but replaces the cylinder with the shape shown at right. Again the part of her graph that represents how the water level changes with time between levels *a* and *b* is shown.



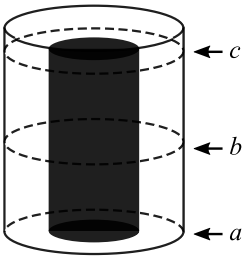
d. Describe how the water level changes over time.



e. Complete the graph so that it represents how the water level changes with time between levels *a* and *c*.

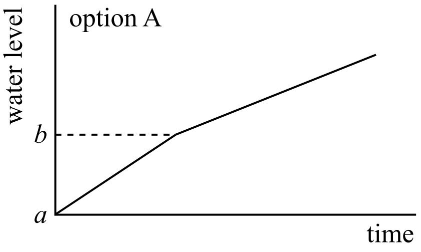
f. Explain why you drew the graph the way you did.

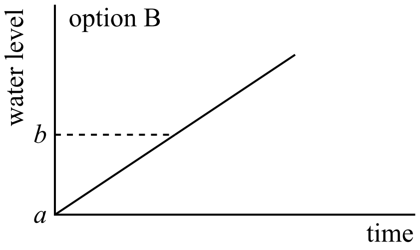
2. A student fills a beaker using a constant stream of water. There is a solid cylinder inside the beaker. The student has marked three levels (*a*, *b*, and *c*) evenly spaced along the beaker. She starts her stopwatch when the water reaches point *a*, at the bottom of the beaker.

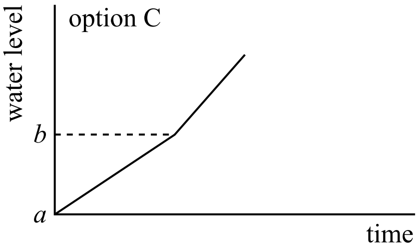


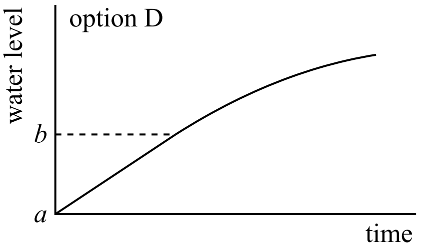
   a. Which of the graphs A–F best represents how the water level changes with time between points *a* and *c*?

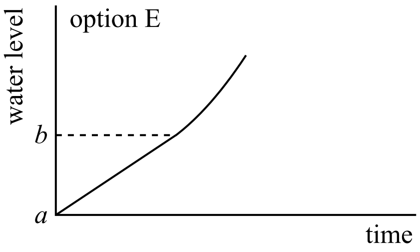
   b. Explain how you made your choice and how you ruled out the other options.

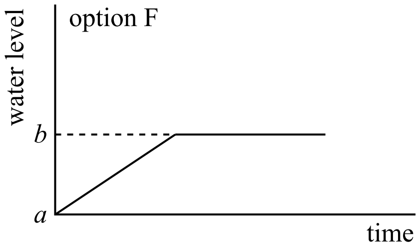


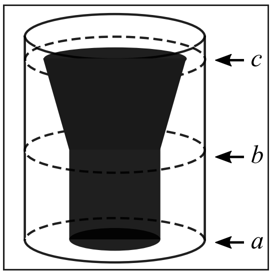










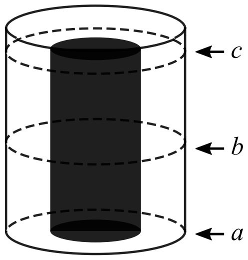


She then repeats the experiment but replaces the cylinder with the shape shown.

c. Which of the graphs A–F best represents how the water level changes with time between points *a* and *c*?

d. Explain how you made your choice and how you ruled out the other options.

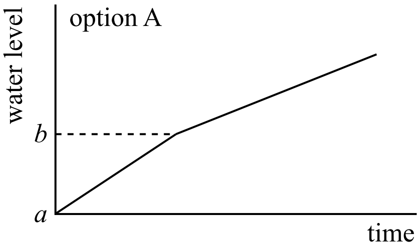
2. A student fills a beaker using a constant stream of water. There is a solid cylinder inside the beaker. The student has marked three levels (*a*, *b*, and *c*) evenly spaced along the beaker. She starts her stopwatch when the water reaches point *a*, at the bottom of the beaker.

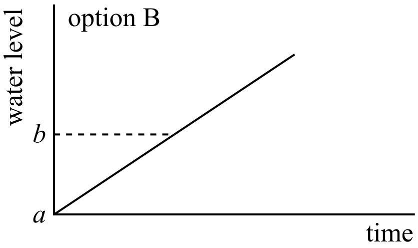


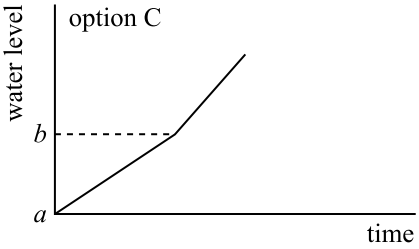
   a. Describe how the water level changes over time.

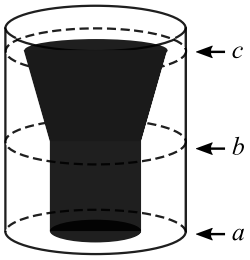
   b. Which of the graphs A–F best represents how the water level changes with time between points *a* and *c*?

   c. Explain how you made your choice and how you ruled out the other options.



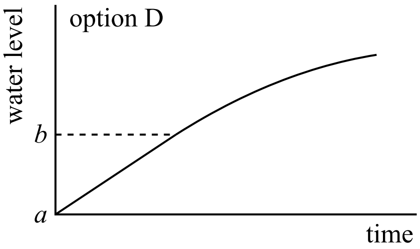






She then repeats the experiment but replaces the cylinder with the shape shown.

d. Describe how the water level changes over time.



   e. Which of the graphs A–F best represents how the water level changes with time between points *a* and *c*?

   f. Explain how you made your choice and how you ruled out the other options.