Department of Physics & Electronics

Teaching Problem Solving: The "Ten Commandments" Approach

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Abstract

The evident need for an intervention to help physics students, especially incoming university students, develop their problem-solving skills led to exploring possible curriculum structures to achieve the goal. A modified curriculum structure of the first-year physics course, including explicit teaching of physics problem solving, was developed and implemented at Rhodes University, South Africa, in 2017. First-year physics students learn to solve problems by implementing the "Ten Commandments" of physics problem solving in their solutions, following a three-stage problem-solving framework. Additionally, students attend whiteboard tutorial sessions where they actively practise using the problem-solving framework in their solutions to physics problems with peers in an environment where help is available. Students are explicitly prompted to use the "Ten Commandments" during the whiteboard tutorials and not prompted for other assessment tasks. Students' solutions to formative physics assessment tasks (problem sets and tests) in the first semester were examined, problem-solving scores were determined using a problem-solving rubric developed in the department, shifts in attitudes and beliefs about physics and solving problems in physics were measured, and relationships between their problem-solving scores and task performance were evaluated to investigate how students adopted the framework and its implications over one semester. The problems issued to students differed in context and difficulty level; as a result, not all of the "Ten Commandments" were applicable to solve all problems, and different combinations of the commandments were applied to different problems. The explicit use of the problem-solving rubric to mark student problem sets was an indirect prompt for students to use commandments when doing their problem sets. As a result, students attempted to implement more applicable "commandments" (mostly partially correct) in their solutions to problem sets than in tests. Moreover, students' solutions to problems show that they used more of the "commandments" they were familiar with from school and less of the new ones, such as drawing diagrams without being prompted, producing algebraic solutions before substituting numbers, and doing dimensional analysis. Problem sets are often assumed to help prepare students for tests; however, correlations between students' problem-solving scores and performance between the two assessments did not give clear indications of whether problem sets were helping to prepare students to solve problems. Lastly, students' attitudes and beliefs also show a negative shift in students' perceptions of problem solving by the end of the first semester. Problem-solving is a skill that develops in stages and over time; therefore, a timeframe longer than one semester is needed to report on significant changes in students' problem-solving habits and perspectives about problem solving in physics. The study results are also important in giving insights into the initial developments of problem-solving skills and teaching problem solving.

Declaration

I hereby declare that this thesis has not been submitted, either in the same or different form, to this or any other university for a degree and that it represents my own work. I know the meaning of plagiarism and declare that all of the work in the thesis, save for that which is properly acknowledged, is my own.

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List of abbreviations

- CLASS : Colorado Learning Attitudes about Science Survey
- CHE : Council on Higher Education
- DBE : Department of Basic Education
- SAIP : South African Institute of Physics
- PER : Physics Education Research

Chapter 1

Introduction

1.1 Background Context

Physics Education Research (PER) is a field where physicists in academic spaces investigate and evaluate ways to improve the teaching and learning of physics. Due to the widely acknowledged role of problem solving in physics teaching, learning, and assessment, the PER community explores problem solving in order to develop and teach problem-solving strategies to students, especially incoming university students. Also, adopting structured problem-solving strategies can help structure the content knowledge and result in improved understanding and performance in physics [1, 2, 3, 4, 5, 6, 7, 8].

The report reviewing undergraduate physics curricula in South African universities by the South African Institute of Physics (SAIP) and the Council of Higher Education (CHE) influenced the modified curriculum for the first-year physics course at Rhodes University. In the report, [9], the South African Institute of Physics and the Council on Higher Education encourage physics departments in South African universities to explore innovative teaching approaches to help students develop the skills expected from a physics graduate. Among the skills outlined in the report, [9], the need to help students develop their problem-solving skills was the most emphasised. The review results resonated with years of teaching observations and frequent tea-time conversations within the Department of Physics and Electronics at Rhodes University, expressing frustrations about students, especially in the first-year class, demonstrating poor problem-solving habits and how these habits affect students' performance in physics assessments. A structured physics problem-solving framework was developed and introduced into the first-year physics curriculum at Rhodes University in 2017 to teach students explicitly physics problem solving and to help them develop the skill for the future because solving different types of non-familiar and complex problems is the number-one future job skill that recruiters in the job market look for from candidates in all fields [6, 10].

1.2 Research Aim

Students are introduced to the problem-solving framework at the beginning of the year. They attend whiteboard tutorial sessions where they actively solve problems with peers in an environment where immediate assistance and feedback is available from the course lecturer and tutors. During the whiteboard tutorials, students are explicitly prompted to use the "Ten Commandments" in their solutions to assigned problems and are not prompted for other assessment tasks. Students' solutions to formal physics assessments (problem sets and tests) were examined, and shifts in their attitudes and beliefs about physics and solving problems in physics were measured to evaluate the impacts of the problem-solving intervention on students' problem-solving habits, and their perspectives about physics and solving problems in physics, respectively.

The project results may be used for further curriculum refinement and proposals for future curriculum development purposes.

1.3 Thesis Outline

Part One of this thesis consists of three chapters (Chapters 2-4) that draw on literature, starting by describing and defining problem solving as a three-stage process in Chapter 2. Since a successful problem-solving experience depends on how well the solver uses their problem-solving toolbox to navigate the problem space to find a solution to the problem, Chapter 3 of this thesis describes the key elements of the problem-solving toolbox. This chapter further discusses the role played by each element of the problem-solving toolbox to an effective physics problem-solving experience and learning of problem-solving strategies. Chapter 4 reviews successful instruction methods that include explicit teaching of problem-solving strategies including physics problem-solving strategies, teaching approaches and environments, evaluation tools, classroom support, and activities included when teaching physics problem solving to help develop students' problem-solving toolboxes and possible scaffolds to supplement the process of learning physics problem-solving strategies to develop the theoretical framework of the study.

Part Two of this thesis, labeled "Attempting a solution", describes and explains the problem-solving framework and the "Ten Commandments" implemented in the first-year physics curriculum at Rhodes University in Chapter 5, including the methods used to collect and analyse data in Chapter 6.

The last part, Part Three, "Evaluating the Solution", presents and discusses the results of this study. The results of students' attitudes and beliefs measurements are presented and discussed in Chapter 7. Students' attitudes and beliefs were measured at the beginning (pre-instruction) and end (post-instruction) of the first semester of 2017, 2018, and 2019; because of this, the discussion of these results is two-fold. Students' pre-instruction results for the three years are used to infer the extent to which the previous schooling has influenced students' perspectives about physics and solving problems in physics. That is to describe the perspectives of our incoming students. In the second part of Chapter 7, students' pre- and post-instruction results for the 2019 cohort are presented and compared to demonstrate shifts in students' attitudes and beliefs about physics and solving problems in physics due to the problem-solving framework. Chapter 8 extends on Chapter 7 and shows external problem-solving shifts from tracking students' solutions from physics assessments in 2019. Lastly, Chapter 9 demonstrates the relationship between students' problem-solving scores and task performance. Unfortunately, the effects of the "Ten Commandments" problem-solving framework cannot be isolated from those of the overall curriculum because the framework is embedded within the curriculum, and we do not have comparison data of a control group, i.e, a curriculum without the problem-solving framework implemented. It is therefore, difficult to separate the root cause of any changes, given that the teaching approach at university differs from the approach used in school.

Part I

Understanding the Aspects of Problem Solving: Literature Survey

Chapter 2

Problem-Solving Stages

In a school context, educators choose the tasks for students to solve and set the difficulty level for each task; however, each student would have different ways of approaching the assigned tasks. Some students would find the assigned tasks easy or hard, depending on their prior exposure to the content and solving similar problems. For example, suppose a student lacks the content knowledge needed to answer a question or does not possess adequate problem-solving skills and strategies to solve the problem. In that case, they will most probably regard the given task as hard [1, 2, 4, 6, 11, 12, 13, 14, 15, 16]. Furthermore, students' attitudes and beliefs about learning and solving problems in a particular course, and their reading and thinking skills also contribute to challenges encountered while attempting to answer the question [17, 18]. Because students bring to the task their knowledge and skills developed from previous experiences, which are usually different for everyone, everyone in the room will have a unique perception of the given task that often differs from that of the educator. Thus, the task rating as hard or easy depends mainly on the interaction between an individual student and the task or question rather than on the task or an educator who sets it [4, 12].

A problem generally represents trouble, perceived difficulty, and obstacles experienced upon interaction with a task or a situation [1, 4, 6, 11, 19, 20]. These create a gap between the initial and goal states, creating a problem space. In a problem space, the solver uses skills and knowledge to overcome all challenges, obstacles, and difficulties while attempting to find a path connecting the initial state to the goal state. The obstacles often result from missing resources needed to understand and solve the problem, being unable to determine what resources are needed to solve the problem, and the inability to use available resources to develop a solution to the problem. The more obstacles and challenges one encounters while exploring the problem space, the more difficult it feels to find the path. A problem therefore, exists when there is a gap between the initial state and the goal state of the task, and the way to cross the gap is not immediately apparent [12].

Problem solving is a goal-directed process of finding a solution to the task. A solution to the problem is a path that passes through the problem space, connecting the initial state to the goal state [6, 12]. Moving from the initial to the goal state is done in three stages, understanding the problem, solution-search stage, and the evaluation stage.

2.1 Understanding-the-problem stage

The understanding-the-problem stage is where the solver explores the presented task in the problem statement in order to define the initial state to form a representation of the problem. Understanding the problem is done in two parts: conceptualizing the problem and constructing a mental representation of the problem.

Conceptualizing the problem involves using existing knowledge to make sense of the words, identify keywords, and hints given to make inferences from the problem statement [12, 17]. A problem statement contains all details about the problem's context and setting, and including the task's goal including some information that will not be necessary to answer the question. Moreover, the solver makes decisions while separating relevant from irrelevant information, thus defining the initial and goal state of the problem [1, 12, 17]. When the solver has conceptualized the problem, all the pieces of relevant information are connected with all the inferences and conclusions drawn to form a mental representation of the problem [17]. A mental representation of the problem can then be further translated into an external representation of the problem on paper, depending on the complexity of the problem.

2.1.1 Representations

Representations are forms in which particular concepts and problems are expressed and communicated, and help the solver extract and use information efficiently [1, 3, 12, 17, 21]. Representations of problems are any relations formed by a solver based on how they comprehend the problem, and these often highlight key relations between quantities and operations in the problem. The solver forms two types of problem representation while solving a problem: internal representations and external representations [1, 12, 17].

- **Internal representations** are sometimes called mental models. They represent how the students store components of the problem in their minds [1, 12]. They also represent the structure of students' physics knowledge that results from links between the key features of problems and underlying content knowledge [1, 12, 17].
- **External representations** are representational formats representing mental models in the external world. The most commonly used external representational formats include pictures, words, symbols, sketches, diagrams, and graphs [1, 3, 12, 17].

Mental representations are the most crucial representations during the problem-solving process because they are the starting point of the process [1, 17]. Mental representations support students' comprehension of physical principles and concepts by providing an associated mental image to these ideas, thus allowing students to have a better understanding of principles and concepts, the elements of the problem, and how they interact with each other [3, 22]. An appropriate and correct mental representation of the problem helps trigger solution procedures by drawing out students' intuitive informal and formal knowledge and strategies, which allow students to connect this knowledge to formal symbolic problem formats (schema-driven problem-solving approach, Section 2.2). Failure to construct an appropriate and correct mental representation of problems results in the process becoming too burdensome and students thinking that the problem is impossible to solve or even solving for a different task [1].

Though some problems are solvable with only mental models, external problem representations become essential for more complex problems, which include most physics problems [1, 3, 23]. External representations help the solver keep track of the solution, remember information, and sometimes notice new relations in the problem that were not explicit in the mental model [1, 12]. Furthermore, producing correct and helpful external problem representations helps increase problem-solving performance by lessening the working memory load [1, 3, 5, 12, 15, 17, 21, 23]. Also, when students fail to solve the problem, their external representations help physics lecturers understand and follow students' thinking and provide appropriate formative feedback that students can apply when solving a similar problem.

The understanding-the-problem stage is crucial in the problem-solving process as it allows the solver to construct a representation of the problem. Students often take this stage for granted and tend to jump to solving the problem, often with a problem representation that is developed based on the surface features of the problem and with little understanding of the context of the problem. Furthermore, students sometimes spend little time engaging with the problem statements and seldom look back at the problem statement even when they are stuck attempting to solve the problem [11]. Hence, their problem-solving difficulties can sometimes be traced to be a result of misinterpretations of the problem statement that often leads to their solving a different problem and making incorrect inferences [1, 12, 17]. Students need to be encouraged and trained to construct, evaluate, and check the appropriateness and correctness of their problem representations because the problem-solving experience depends heavily on these two factors. The correctness and appropriateness of any problem representation increase students' chances of solving the problem correctly.

2.2 Solution-search stage

In the solution-search process, the solver explores the problem space to find a path that connects the initial state to the goal state. From this point, success in crossing the gap depends on the problem representation, the adequacy of the tools in students' problem-solving toolboxes, and the effectiveness with which they carry out the actions and tasks required by the problem-solving process [1, 12, 24]. Solving problems using schema-driven approaches and formal problem-solving strategies are commonly used to solve physics problems.

Problem schemas are information packages constructed from organizing the knowledge gained from problem-solving experiences. Schemas contain information about properties used to recognize, interpret, and solve different problem types [5, 6, 12, 24, 25, 26]. The different problem schema categories include information about critical features used to judge and relate the current problem to a particular problem type, problem representations, and possible interrelated solution procedures, as well as conditions in which to use them [5, 6, 12, 24, 25]. Keywords and problem representations trigger problem schemas, allowing the student to identify the problem type. Once a solver has identified the problem type, the solution search process becomes an activity of mapping an existing problem schema onto a current problem [3, 5, 6, 12, 24]. Because students often rate problems as similar based on the surface objects and terms rather than concepts used to solve the problem, and their knowledge consists of disconnected facts without any conceptual links, the schema-driven problem-solving approaches are most effectively used by physics experts [5, 22, 24]. Students then use alternative search methods to solve problems. Some of these are described below [11, 22, 27].

Problem-solving strategies include techniques composed of a set of actions or tasks offering guidance to a systematic approach, allowing students to proceed from the initial state through the problem state to reach a solution [12, 13, 24, 28]. Because problems differ in context and difficulty level, students need to be aware that using these does not guarantee a correct solution to the problem or any solution. Hence, combining different strategies sometimes increases the probability of arriving at a solution [24, 28]. Possible methods used for solving problems in physics are:

- **Analogy:** This method uses knowledge of past problem-solving experiences to solve new problems [28]. Analogy involves looking at examples that share some aspects with the current problem and mapping the solution of the example problem to the current problem. Effective use of this strategy depends on how students qualify problems as similar because it affects how they apply the knowledge gained from problem-solving experiences to solve new problems [5]. The hunt for similar problems and their solutions occurs when students solve homework problems. Students often use solutions to example problems as templates to solve the current problem [1, 24].

- **Means-end-analysis:** When using this method, students start by assessing the gap between the initial and the goal state by identifying the givens and unknowns [28]. After identifying the goal, students start their solution search by choosing an equation containing variables representing the goal and the given; sometimes they choose equations without thinking about their applicability to the problem. If the chosen equation contains other unknowns that cannot be calculated directly using the given information, they choose different equations to find the unknowns. After students have solved for these unknowns, they go back to the first-picked equation and insert the calculated values of unknowns to find the goal [1, 5].

- **Trial-and-error:** Generally, the trial-and-error strategy is used when the solver is faced with a new challenging problem and cannot recognize meaningful patterns to generate a solution from past problem-solving experiences [6, 12, 28]. The solver then generates and explores different possible solution paths based on assumptions and tests one solution path at a time to see their applicability [6, 12, 28].

Students often use this strategy for slightly different reasons. They use this when they do not know how to transfer the template solution of previously worked examples to solve the current problem. In tests and examinations, students use trial and error for previously seen questions and when they can only recall parts of the solution. Because students know the answer, they spend time trying different equations, checking and monitoring their solution to reproduce it. Students often struggle to solve similar or previously worked problems because they focus on surface features and terms rather than extracting a knowledge structure that includes the central ideas from their problem-solving experience [29]. Also, students would rather watch someone else solve a problem they did not get a correct answer to or look at a published solution than try to understand the process of solving the problem.

Amongst the above three strategies, the means-end-analysis strategy is the most used strategy by students. The means-end-analysis strategy is suggested to be ineffective in learning to solve different problem types and improving students' conceptual knowledge [1, 11]. This strategy is considered a mechanical way of solving problems because it directs students' attention to thinking that solving physics problems means they have to recursively perform calculations and manipulate different equations with almost no planning or careful analysis of the problem. Therefore, students miss the essential details about the problem [1, 5, 24]. As a result, teaching at university level aims at teaching students alternative problem-solving strategies that involve applying conceptual knowledge, critical thinking, and careful analysis of the problem information to progress with the solution.

2.3 Evaluation stage

The evaluation problem-solving stage can be thought of as the stocktaking stage, where the solver consolidates all gains from the problem-solving experience [12]. Ideally, here, the solver reflects on the entire problem-solving experience after following all the necessary steps to solve the problem and having arrived at a solution to the problem. The words 'a solution' are used here because arriving at a solution does not necessarily mean it is a correct solution for the problem. Ideally, all solutions to problems need to be validated before they can be qualified as actual solutions to the problem. Validating a solution involves evaluating the correctness of the solution by looking back at all the steps and actions taken during the process to check if every action taken is justifiable and if all steps follow each other logically. Furthermore, the solver then looks back at the problem statement, problem representations, assumptions, and inferences used to develop a solution to check if they have applied their knowledge correctly. Lastly, the solver checks whether their 'solution' to the problem can reproduce the given conditions, agrees with all assumptions made, and checks for and corrects any errors in the solution.

The reflection aspect of this stage also allows the solver to think about, compare, and recognize similarities and differences in the state of their problem-solving resources before and after the problem-solving experience [11, 12]. Because problem-solving highlights conceptual relationships symbolically and visually, the problem-solving reflection task allows students to associate relevant problem representations to the knowledge used in solving the problem [29]. During this stage, the students may notice new developments in their problem-solving resources that may represent changes in conceptual, strategic, and procedural knowledge that is often linked with conditions as to when and how to apply knowledge in the future and allows students to extract and develop problem schemata (in Section 2.2) to solve similar problems in the future [11, 12, 13, 17, 25, 29]. Lastly, a successful problem-solving task may boost students' confidence, resulting in positive changes in attitudes towards problem solving and helping students strengthen links between their knowledge.

CHAPTER 3

Problem-Solving Toolbox: Resources Needed for a Better Problem-Solving Experience

To overcome obstacles, challenges, and troubles encountered while finding a path connecting the initial state to the goal state (a solution or answer to the question), a set of tools that will enable students to manoeuvre through the problem space is needed. Success in problem solving depends on students' ability to recognize the tools needed to solve the problem, how they use available tools in their toolbox and how they regulate the influence of affective factors during the process. The following sections describe how knowledge, skills, and affective factors contribute to an effective problem-solving experience.

3.1 Knowledge

Knowledge plays a crucial role in problem solving. It enables students to comprehend and construct the meaning of the problem statement, and every problem-solving stage requires different knowledge to be applied together with other tools. Because students are assigned problems based on a particular physics topic, they need to have acquired some knowledge about the topic before they are required to apply it to solve problems, otherwise they will struggle to determine the correct knowledge needed to solve the problem [1, 6, 12, 13, 17, 30].

The knowledge required to solve problems is referred to as the knowledge base, and it is the knowledge that students activate or retrieve when solving problems. The knowledge base consists of physics principles, physical laws, generalizations, methods, procedures, and other relevant information that can be used to solve problems. The knowledge base components fall within four general types of knowledge: factual knowledge, conceptual knowledge, procedural knowledge, and metacognitive knowledge [31]. The content knowledge that is often presented in the classroom usually consists of procedural knowledge, factual knowledge, and conceptual knowledge, known as domain-specific knowledge [31]. Metacognitive knowledge is a general type of knowledge. Four general types of knowledge are discussed below :

- **Factual knowledge** is considered the language used in the relevant subject and that students have to learn to communicate and solve problems in the domain or subject [13, 31]. This knowledge consists of the terminology, basic definitions, laws, dates, events, and people, including specific details used to explain phenomena in the field. Many relations used in the subject are derived from factual knowledge [31].
- **Conceptual knowledge** includes different models and structures developed from classifications, categories, and generalizations of concepts and principles [20, 31]. Furthermore, conceptual models represent understanding meanings, relations, and links between different concepts and principles [29, 31].
- **Procedural knowledge** includes the knowledge of skills, algorithms, techniques, and methods used to manipulate different concepts, as well as knowledge of the criteria used to determine what to do, when, and why [11, 13, 31].
- **Metacognitive knowledge** is awareness of one's cognition and understanding of one's thinking processes and products [32, 33]. Despite having conceptually structured domain knowledge and experience in solving different problems, physics experts are also successful at solving problems because of their developed metacognitive knowledge [2, 5].Throughout the problem-solving process, experts continuously think about what the problem is asking and what strategies to use to solve it effectively [2]. They use this knowledge together with the knowledge about one's strengths and weaknesses related to the task to plan and decide on the best cognitive resources within one's thinking capabilities to complete the task [31, 32, 33, 34, 35]. Consistent monitoring and regulation of their progress allow them to be more in control of the solution path and be able to catch and correct errors [11, 2, 25].

Knowledge is accessed and applied effectively during problem solving when students possess adequate conceptual knowledge about the topic and understand the links and relations between different concepts, including when and how to use the concepts. The problem statement often has keywords revealing hints and assumptions about problem situations when their meaning is unpacked. The information embedded in the keywords often includes knowledge that relates problem situations to different concepts applicable to solving problems. For example, *"uniform motion"* is a key phrase that appears in first-year-level physics problems, and inferences about the object's velocity, and the acceleration of the object can be made from it. When the students understand these words and their relation to other concepts and principles, all this knowledge will be triggered from memory to explore possible solutions for the problem.

In class, content knowledge and strategies that model the conceptual and qualitative reasoning valued in physics are presented, and students are given more problems to solve outside class. However, students, especially at introductory physics levels, often have difficulties recalling and applying knowledge to solve problems. Students have difficulties solving problems because their knowledge is retrieved from memory as single blocks without any relation to other concepts, and they cannot extract crucial information about the problem from the keywords [5, 11, 24, 29, 36]. Their inability to better monitor and regulate their thinking during the problem-solving process also contributes to their difficulties in deciding what knowledge to use to solve problems and their success in solving problems [11, 33]. Thus, it is not the amount of knowledge presented to students but how it is presented and connected in memory that facilitates a successful problem-solving process [6, 13].

3.2 Skills

The differences in nature of problems, obstacles, and difficulties encountered while finding a solution to problems require different combinations of skills to be applied during the process [1, 4, 5]. The skills used during problem solving include anything that can affect the solver's ability to solve the problem and are categorized as either *have*, *do*, or *skills needed to survive the problem-solving process* [4]. The skills in these categories include cognitive and metacognitive skills, domain-specific knowledge, and knowledge from other domains. Below a short outline and description of the skills are given :

- **"Have" skills:** are things that students should have and know before interacting with the problem; otherwise, solving the problem would seem impossible. Students need to *have* cognitive skills and previously known physics facts, so they can read and understand the language used in the problem and domain, make sense of information, and effectively apply their thinking skills to comprehend the problem and generate inferences and relations not explicitly stated in the problems [4, 5, 37, 38]. Many relations in physics are expressed as mathematical equations, and many problems involve performing a calculation or deriving expressions; hence, students should also be able to formulate equations, use mathematical operations, and make sense of numbers when solving physics problems [4, 37, 38]. Lastly, students need to be able to use their knowledge of strengths and weaknesses in order to decide on strategies to use, within their abilities, effectively to solve the problem.

- **"Do" skills:** include the solver's ability to gather information, determine what concepts, principles, and relations are needed to solve the problem, identify the givens and unknowns, and put the pieces of information together while drawing appropriate representations [4, 5]. As these skills frame the problem-solving process and form foundations for problem-solving techniques, many problem-solving instruction methods focus mainly on helping students develop these skills.

- **Skills needed to survive the problem-solving process:** The effectiveness of learning and problem solving depends not only on cognitive and metacognitive factors but also on personal initiative and persistence [39, 40, 41]. Students' attitudes and beliefs about the subject (physics) as well as problem-solving and affective factors influence interest, effort, and willingness to solve the problem, mediate whether they apply their knowledge, how they interact with the task, and their performance. Affective factors include people's emotions and attitudes about themselves or their surroundings and can influence students' perceptions of physics and problem-solving problems in physics [42]. The problem-solving process, especially for complex problems, requires regulation of thoughts, feelings, and actions and a driving force (motivation) toward wanting to solve the problem because, in some instances, a student may be unable to use known strategies because do not enjoy carrying them out or do not feel that the outcomes are worth the effort.

The skills used during the problem-solving process have varying importance depending on the problem.

CHAPTER 4

Helping Students Develop their Problem-Solving Toolbox using Constructivist-based Approaches

"The only way to learn a skill is by doing it!"
- John Dewey

Due to the nature of problem solving, the best environment for teaching and learning problem solving is one that allows students to actively engage in problem-solving activities rather than passively watching someone else solve problems [43, 44, 45, 46, 47, 48, 49]. Students are more likely to adopt newly taught problem-solving strategies if they are described in detail and explicitly taught when and how to use them with the same seriousness as the content. Teaching problem solving requires that instruction creates problem-solving experiences and provides feedback so that students can actively learn to use the strategies being taught. Because students are expected to develop their problem schemas and problem-solving toolboxes from the problem-solving experiences they are exposed to, problem-solving strategies are best taught in a constructivist-based teaching model instead of a traditional tell-and-show teaching approach.

Constructivist-based teaching and learning approaches employ Bruner's, Piaget's, and Vygotsky's constructivist theories, that share the view that learning happens when students are actively engaged in the process of creating their knowledge [50, 51, 52, 53]. In a constructivist class arrangement, students actively learn, relearn, and even unlearn, while trying to make sense of the material given to them through interaction with the environment and other students [50, 52]. In this case, physics lecturers and tutors become learning coaches that guide students in their learning processes instead of presenting all information as they would in a traditional class arrangement [2, 51].

Constructivist-based class arrangements often rely on peer-collaborative instruction methods rather than the usual telling-paradigm teaching approach used in traditional teaching methods. Peer-instruction methods often employ "each-one-teach-one" teaching strategies by allowing students to actively learn from interactions with one another and the environment in which they operate. Furthermore, peer-collaborative learning and problem solving usually involve grouping students in small groups because smaller groups provide an environment of trust allowing students to be comfortable to express their struggles with the material without being ridiculed, and explanations from fellows are often simpler than those of lecturers [40, 48, 46, 54]. Hence, students are known to learn better in these environments than in bigger classes.

In class, students work together, sharing procedural and conceptual knowledge as they engage in learning and problem solving. Because each group member contributes their different ways of thinking, understanding concepts, and ways to solve physics problems, students may learn about more straightforward ways of learning and solving problems they can apply when doing individual work. The quality of information shared within a group and the quality of solutions produced by the group depends on the dynamics of the groups. Problem solutions produced by students as a group are often of higher quality than those produced by an individual student, only if the group consist of students with mixed abilities [46, 47, 48, 49, 54]. Many lecturers often opt to assign students to groups based on their abilities; however, this way is not always effective towards learning because if the range between students are too wide the low ability students would become too shy to participate and remain in the shadows of those of higher ability. On the other hand, groups formed by students are sometimes not productive but allowing them to choose peers with whom they are comfortable working helps facilitate more open and honest discussions amongst themselves as well as creating an environment of trust [44, 55, 56].

With this constructivst framework in mind, the lecturers in the department of physics and electronics developed the "Ten Commandments" problem-solving approach described in Section 5.1. Students actively solve problems in whiteboard tutorials, as described in Section 5.3. Assessment problems are specifically chosen to expose students to different problem-solving experiences so they further practise using the framework. Additionally, students get immediate feedback from lecturers and tutors during whiteboard tutorials and continuous feedback for their assessment tasks to supplement their learning.

Part II

Attempting A Solution

Chapter 5

Teaching Problem Solving: The "Ten Commandments" approach

Students taking first-year physics courses at university often join these classes with both poor problem-solving skills and poor understanding of physics concepts and principles [9, 20, 28]. The review report by the Council on Higher Education and the South African Institute of Physics in 2015 [9] reveals that physics lecturers in South African universities know of students' incoming problem-solving and learning abilities and limitations and often say that incoming students are unprepared to be at university. Even so, many physics lecturers continue to expect students to demonstrate expert-like problem-solving habits simply because students have seen how example problems are solved by lecturers in class.

Since the publication of the joint Undergraduate Physics Review Report by the CHE and SAIP in 2015 [9], various physics departments in South African universities reviewed their curricula and started exploring possible innovative teaching approaches to help students develop the skills they are expected to have developed to pursue postgraduate physics studies and other careers after graduation. The Department of Physics and Electronics at Rhodes University responded to the report by developing a problem-solving framework and explicitly teaching problem solving to first-year physics students while establishing the Physics Education Research team in the Department.

5.1 Rhodes University Physics Department's Problem-Solving Framework

Many incoming students solve physics problems using the plug-and-chug approach, which is how they solved them at schooling. This strategy involves solving physics problems by choosing an equation, substituting values, and doing mathematical manipulations with numbers to get to an answer (as described in Section 2.2). When using this strategy, students usually choose an equation based on the given and unknown variables in the problem, sometimes with little or no understanding of the concepts related to the problem. Because this strategy is used without qualitative reasoning, the plug-and-chug problem-solving approach constrains students' development of problem schemas and conceptual understanding because it directs students' attention toward mathematical manipulation of equations and numbers rather than using qualitative reasoning and analysis to develop solutions [1, 2, 5, 57]. The use of conceptual knowledge and qualitative reasoning to develop solutions is crucial to the construction of effective problem schemas. Refer to Section 2.2.

The problem-solving framework, developed by a member of the lecturing staff, is taught to the physics first-year class at Rhodes University and aims to help students develop their problem-solving skills. Like existing problem-solving strategies, this framework teaches students to solve problems using concept-based problem-solving approaches as well as qualitative reasoning rather than plug-and-chug. Furthermore, the framework promotes translation between multiple representations during problem-solving, where students learn to translate between different problem representation formats while progressing between the three identified critical stages of problem-solving shown in Figure 5.1 [58].

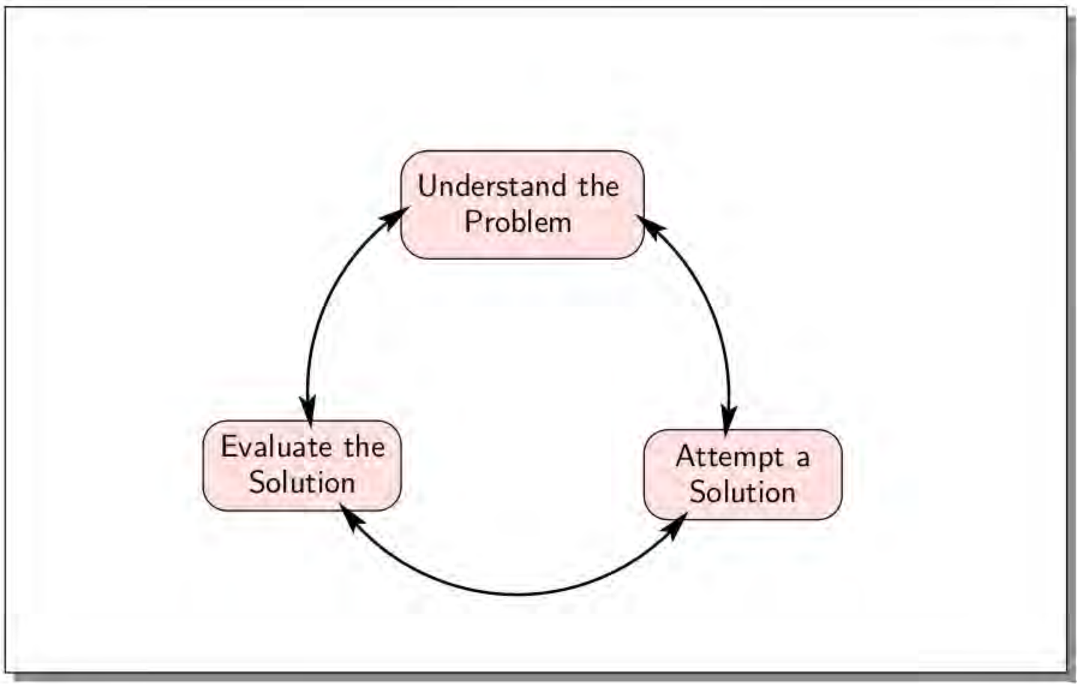

Figure 5.1: The three-stage problem-solving framework introduced to the first-year curriculum as developed by Giovanonni [58].

This framework describes the problem-solving process in three rather than four or five steps described in many problem-solving strategies in literature [46, 59, 60, 61]. The problem-solving framework takes the viewpoint that problem solving is "what you do when you do not know what to do," a definition by Wheatley [62]. The assumption is that students use the framework as a guide because they do not know what to do, and the framework guides them to use already existing information about the problem and make decisions about the next step to try using qualitative reasoning. Students rely on their metacognitive abilities to constantly think about their current state and monitor and regulate their progress with the task. The problem-solving process involves continuous planning and execution as students develop a solution. As a result, this framework does not have planning and executing the plan as stand alone stages of problem-solving but incorporates some aspects of the planning steps in the understanding-the-problem stage and the attempt-a-solution stage.

Finding solutions to most physics problems, especially complex problems, is usually not a straightforward process, and following a series of problem-solving steps in their order does not always guarantee a solution after performing the last step. Some backtracking between the different stages of problem solving may be required, especially when one does not know what to do. For example, while attempting to find the solution, students may discover that they have reached a dead-end of the initial solution path and have to backtrack to representing the problem and even to the problem statement to see whether they have missed any essential information about the problem [1, 24]. Backtracking allows students to notice new relations that they may have missed and rectify the mistakes and errors, which may, in turn, lead to a new solution path. The bi-directional links between the problem-solving stages therefore, explicitly emphasize the non-linearity of solving physics problems. Notice, in passing, that this circular, bi-directional structure also mirrors the way that the "scientific method" is often presented to students.

5.2 Implementing the Ten Commandments of Physics Problem Solving within the Framework

Developing a solution to the problem requires a toolbox, and each stage of problem solving requires a different set of tools. Students are provided with a set of guidelines to help them construct and explore different problem representations required by each problem-solving stage. These guidelines incorporate skills and heuristics that benefit problem solving and help trigger students' knowledge. The guidelines that may be applied in each problem-solving stage are shown in Figure 5.2 and are referred to as the "Ten Commandments" of physics problem solving (Figure 5.3).

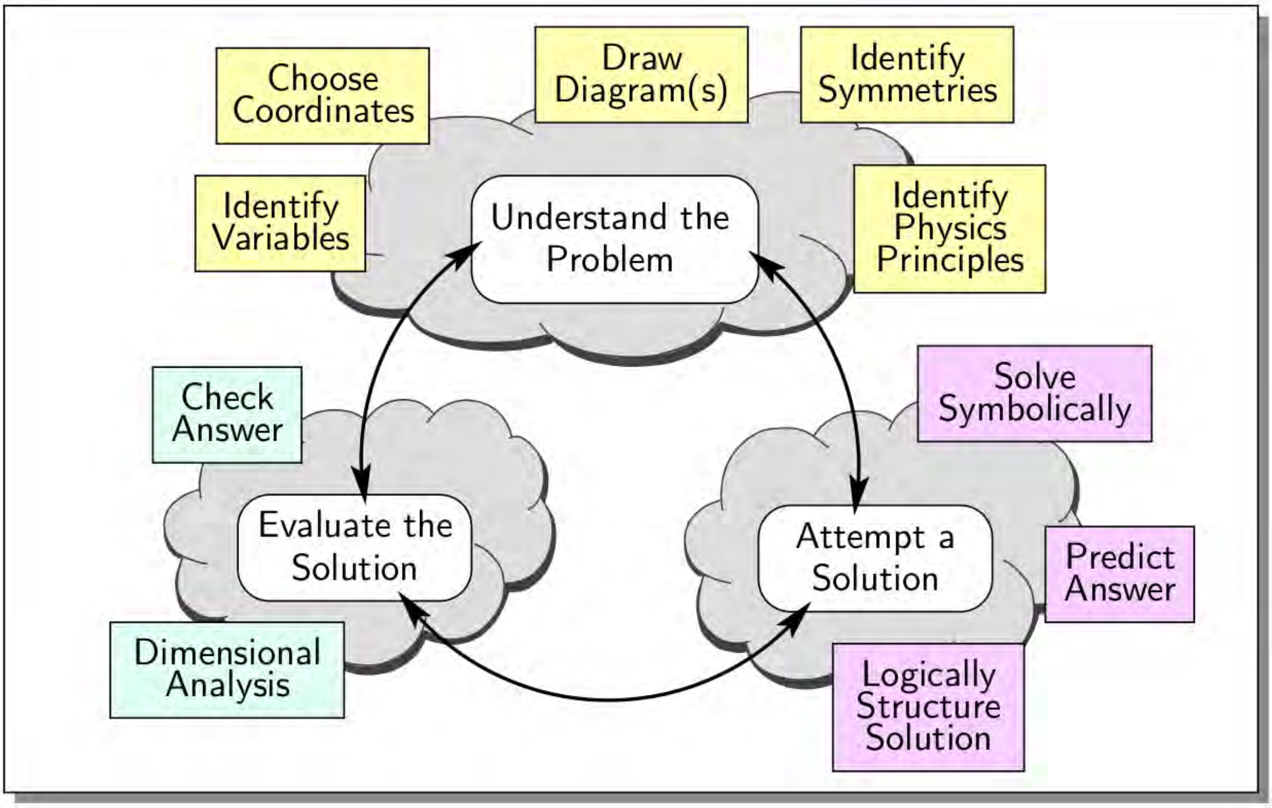

Figure 5.2: The commandments that students may apply grouped by problem-solving stage [58].

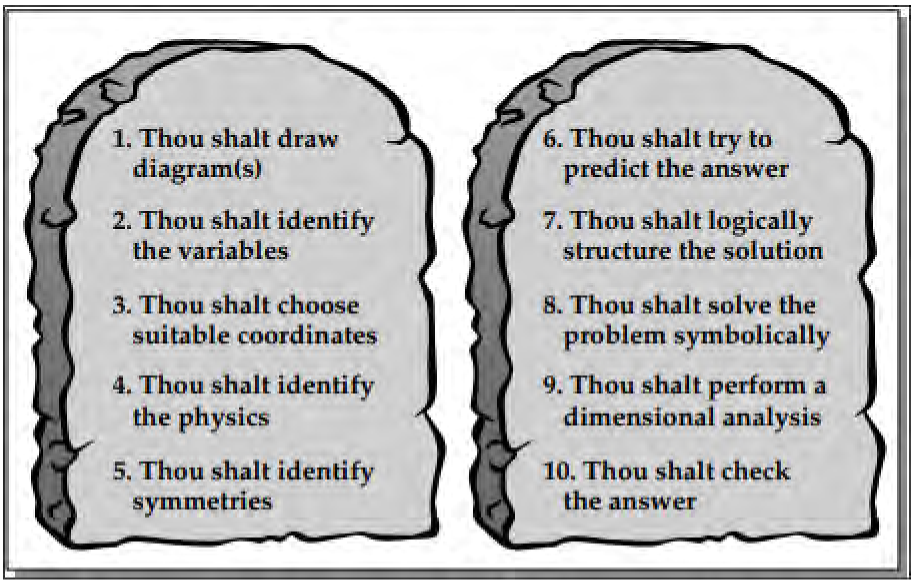

Figure 5.3: The "Ten Commandments" of physics problem solving [58].

5.2.1 Understanding the problem

The understanding-the-problem stage involves translating the problem statement, usually in word form, to an external diagram that highlights only information critical to solving the problem and interactions between the objects in the problem. External diagrams that can be used to represent physics problems include, but are not limited, to free-body diagrams, field-line diagrams, before-and-after diagrams, and graphic representations that show relationships between variables in question.

The following "commandments" can be applied to help students choose information relevant to the problem and construct an adequate representation of it (see Figure 5.2).

- The first commandment, **Thou shalt draw diagrams(s)**, intends to explicitly encourage students to construct and work with external representations of problems even when not prompted by the question to draw one. Producing an external diagram instead of working with mental representations helps reduce memory load so that students can direct their mental resources towards solving the problem rather than having an added load of remembering the aspects of the problem. Furthermore, external representations help students organize information about the problem, see relations that may not be obvious from the mental representation or problem statement, and trigger knowledge essential to solving the problem, i.e., problem schema (refer to Section 2.2). Lastly, producing diagrams along with solutions makes it easier for markers to identify errors and provide feedback to help them improve how they draw and use representations during problem solving. To implement this commandment, students are encouraged to produce fully annotated diagrams with important information extracted or inferred from the problem statements - Figure 5.4 is an example of a free-body diagram to be produced by students.

- **Thou shalt identify the variables:** *Variables* are symbols and letters used to represent the physical quantities in the problem and are also used as place values for physical quantities when numerical values of the quantity are not specified. Identifying variables can be done as part of the drawing as shown in Figure 5.4. The symbol θ is used for the angle of elevation of the hill with respect to the horizontal. Additionally, f_k and a denote the friction force on an object as a result of contact with the surface and acceleration of an object, respectively.

  In the case of a many-body problem where a physical quantity is defined for all objects or a before-and-after problem where we are interested in the value of a physical quantity at two different times, students are taught to use different variables or sub-scripts to differentiate between the variables relating to quantities of different objects. For example, in collision scenarios, there are usually two objects for which mass is defined. In such a case, students could define the objects' masses as m_1 and m_2 or m_t and m_c, for each example.

  Another way of identifying variables is by listing knowns and unknowns before an equation. This is a conventional way of defining variables that appears in most student

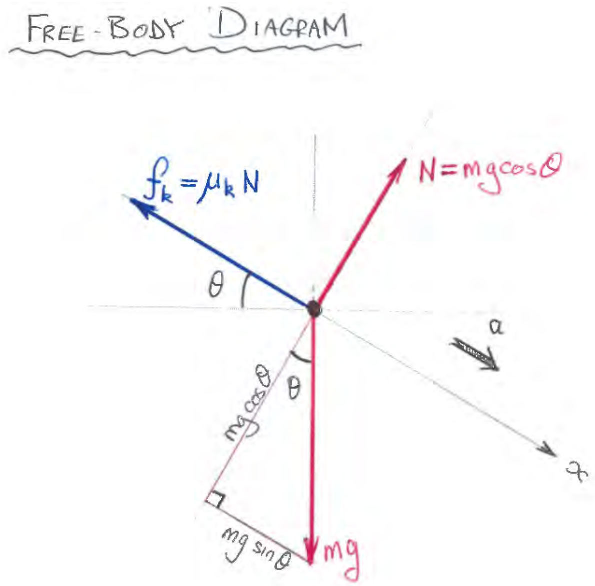

Figure 5.4: The free-body diagram showing all external forces acting on a car as it slides down a hill with friction. Each force is given a label that will be used to refer to it in the solution, with arrows depicting information about the direction in which the force is acting. Furthermore, the components of the gravitational force are drawn using a different line because they represent the effects of the force on the different axes as a result of the angle. The bold arrow below the a variable gives information about the direction of acceleration . Lastly, the x-axis line represents the coordinate system that the solver will be using along the direction of motion.

solutions because they were taught to do this at school. The units associated with each variable can remind students of the physical meaning of the unknown quantity for which they are solving. Thinking about *variables* leads to thinking about mathematical relations that can be used in the later stages to solve the problem.

- **Thou shalt choose a suitable coordinate system:** Students define the coordinate system by drawing a set of axes on the diagram and putting an arrow indicating direction as in Figure 5.4; or the reference direction can be specified as "taking upwards as positive" (for example) before performing the calculation. The coordinate system helps the solver keep track of the different directions of vectors while working in reference to one direction. This task eases the load of having to remember all the different directions.

- **Thou shalt identify the physics:** Many physics principles and concepts are written in mathematical forms to show relationships between different physical quantities that describe a system. Thinking about what physics principles and concepts are applicable to the problem helps students decide how information in the diagram can be translated to mathematical relations. Furthermore, encouraging students to think about the principles applicable to solving the problem helps trigger relevant conceptual knowledge to develop solutions using qualitative reasoning. Also to pick principles and concepts allows students to construct problem schemas that categorize problems by physical principles applied to solve them rather than the objects in a problem.

- **Thou shalt identify symmetries:** Symmetries are mathematical or physical features of the system that are known to remain unchanged under some transformation [63]. A system is said to be symmetric if it can be divided into two or more identical pieces, and the solution of one piece can be readily used as the solution to the other pieces [63]. Therefore, the knowledge of any symmetrical behaviour of physical systems can be used to derive new solutions for the system by enabling students to eliminate unnecessary information from the problem. Moreover, symmetries help choose a suitable coordinate system creating a possibility of needing only to work out 'half the problem'. Time symmetry is an example of symmetry most discussed at school when analyzing objects in free fall. In the first semester of Physics 1, students also encounter rotational symmetry, which should lead them to choose a polar or cylindrical system to solve rotational problems.

5.2.2 Attempting the solution

In the context of the study, this stage aims to teach students to use the information they have already acquired about the problem to derive mathematical relationships that can be used to solve for a variable in question.

- The commandment **Thou shalt solve the problem symbolically** aims to encourage students to perform symbolic manipulations of the equations and substitute the numbers at the end when they have a symbolic expression of the variable for which they are solving rather than directly substituting the numbers in the equation and manipulating the numbers to get to an answer, which is how they are taught at school. Symbolic solutions allow students to predict the system's behaviour and comment on dependencies when one of the variables changes from the information presented without recalculating for the new scaling [37, 64, 65]. Symbolic solutions make it easier to perform a dimensional analysis, evaluate special cases and upper and lower limits, and make higher-order corrections.

- **Thou shalt predict the answer:** Thinking about the limiting cases, overall behaviour, and constraints of the system can be used to give insights or draw conclusions about the behaviour of the system. Another aspect of predicting an answer includes students commenting about the reasonableness of their answer, such as adding a comment on whether their answer is too big or too small. Comments like these occur after students have checked their answers and do not have time to rework their solutions and show that the students have thought about the range of their answers.

- **Thou shalt logically structure the solution:** The logical structure commandment encourages students to produce easy-to-follow and logical solutions. These include correct use of mathematical operations, consistent use of variables and directions, and conceptually correct logical arguments and reasons for actions.

5.2.3 Evaluating the solution

The evaluating-the-solution stage indirectly steers students' attention towards reflecting on their problem-solving process by requiring them to check their solution before they can say they are finished solving the problem. The benefits of reflecting on the problem-solving process are discussed in Section 2.3. The following commandments can help students to evaluate their solutions.

- **Thou shalt perform a dimensional analysis:** Students are always encouraged to substitute numbers with units if the question requires a numerical value or do a dimensional analysis of their symbolic solution. This way, students can see the units or dimensions which cancel to those of the variable for which they are solving. Also, dimensional analysis enables students to see and understand different ways of expressing a physical quantity and how it is derived from different expressions. For example, force can be expressed in various ways depending on the context, and students are most familiar with the expression $F = ma$ and may not recognize the quantity if expressed differently. Dimensional analysis is helpful in this case.

- **Thou shalt check the answer:** Checking the answer involves checking that the answer is written with the correct significant figures and the correct units. Because arriving at a solution does not necessary mean it is a solution to the problem, students are encouraged to check that their answers are consistent with the initial conditions of the problem and with the prediction of the answer.

The "Ten Commandments" are grouped based on the stage in which they are most applicable, as shown in Figure 5.2. The order in which these commandments are applied depends on the nature of the problem and how students want to progress in their search for a solution. The nature of the problem also dictates the combination of commandments used to solve it. For example, calculation problems would require students to check for significant figures. However, checking for significant figures does not apply in questions where symbols represent values instead of numerical numbers. Lastly, the cyclical nature of this problem-solving framework allows a more flexible approach to solving problems.

5.3 Curriculum Changes as a Result of Teaching Problem Solving

One can only learn to use new problem-solving approaches if one actively engages in problem-solving experiences rather than only watching someone else solve problems. As a result, teaching problem-solving strategies requires instruction to provide an environment of support where students actively learn to solve different types of problems using the strategies being taught, see the theoretical framework in Chapter 4. Since this cannot be optimally achieved in traditional teaching arrangements where knowledge and problem solving are simply presented to students, structural changes in the first-year physics curriculum at Rhodes University were made to accommodate the explicit teaching of the problem-solving framework within a constructivist framework and to allow for extended, active problem-solving sessions.

Before 2017, the Physics 1 class had four 45-minute lecture slots and one 45-minute tutorial slot during the morning each week. The tutorial groups were composed of up to 15 students per tutor. The tutors were lecturers in the department. Students were given weekly tutorial problems as homework before the tutorial session. Solutions to these problems were discussed during the tutorial sessions and posted on the online course page for future reference.

In the year I did Physics 1, 2013, we were not required to submit our solutions to tutorial problems. As a result, some students in our class would attend the tutorial sessions with little or no attempt to solve the problems and would attend the session merely because it was a compulsory course requirement.

Though the groups were about the same size, the tutorial sessions were conducted differently in each group. In one group, students would get to the room and find final answers, not detailed solutions, to the problems already written on the board. Students would then be asked if they had questions regarding the tutorial problems or the answers on the board. If students had questions, the tutor would discuss them; otherwise, the tutorial would be dismissed, assuming everyone understood and could do the problems. Most of the time, students would take advantage of this and say they had no questions to shorten the session.

In another group, the tutor would not write answers on the board and would wait for students to ask questions. The tutor would ask questions to trigger discussions about the problems among students while solving the problems with them. The tutor would outline critical parts of the problem and take students' questions as the tutorial progressed. In this group, the tutor would solve as many problems as time allowed, with varying amounts of interaction with the class.

During this time, students were still primarily passive in their learning to solve problems, and they were not explicitly taught about problem-solving strategies but were still implicitly expected to solve problems in a particular way. Students had to either stick to what they thought worked, meaning their incoming problem-solving approaches, or learn the desired problem-solving trait by taking note of the small problem-solving features they saw in tutorial solutions or when the lecturer solved problems in class.

A new curriculum structure for the Physics 1 class was introduced in 2017. This structure shifted from a mainly traditional teaching method to a hybrid approach. This hybrid method involves a traditional lecture setup and peer-collaborative whiteboard tutorials. During whiteboard tutorial sessions, students actively engage in problem-solving experiences as they learn to use the newly taught problem-solving framework. The key differences between the two structures are highlighted in Table 5.1 and explained below.

Table 5.1: The differences between the old and new curriculum structures introduced in 2017.

Before 2017	From 2017 and onward
4 morning lecture slots	5 morning lecture slots
One 45 minute tutorial slot every week	3 hour whiteboard tutorial every third week
No explicit teaching of problem solving	Explicit teaching of problem solving
Largely passive learning	More engaged active learning

- The weekly tutorial sessions were replaced by three-hour-long whiteboard tutorial sessions roughly every third week, with five sessions in a semester, and these sessions are in the afternoon. The sessions were timed to occur before a course test is due to be written and after most of the content of the test is covered in lectures. During the whiteboard tutorials, students group themselves into groups of three or four and work together to solve problems in a setup shown in Figure 5.5. Tutors and the course lecturer are available in the room to guide students using the "Ten Commandments" and address other conceptual issues that students may have. The tutors are senior physics students.

Figure 5.5: Whiteboard tutorial session with tutors and a lecturer pointed with red arrows.

The whiteboard tutorial problems mostly come from textbooks but differ from the typical short and well-defined end-of-chapter problems. These problems are intentionally complex and conceptually challenging to students, which pushes them to adapt to solve unfamiliar problems and realize the benefits of using the newly taught problem-solving framework when they do not know what to do.

The whiteboard tutorial sessions encourage students to collaborate and share knowledge while learning to solve problems using the problem-solving framework. Using whiteboards provides students with limited working space, constraining them first to discuss how they will solve the problem and their next steps before they can write on the whiteboard. At the same time, the whiteboards provide a bigger space than a piece of paper so that all students can see and contribute at once, and tutors can assess and follow students' progress and address students' struggles as they occur rather than waiting for them to ask questions. To further support collaborative work, each group is given one problem to solve at a time and can only progress to the following problem after solving the current one. This way, students cannot split the problems and have other group members solve different problems. Typically, about four problems are solved in an afternoon.

The shift to whiteboard tutorials resulted in a gain of the extra teaching slot. Lecturers can use this extra time to do more examples, demonstrate the use of the problem-solving framework in class, and further encourage students to use it.

- Instead of having solutions to the tutorial problems discussed weekly during the tutorial sessions, weekly problem sets are implemented. The problems in weekly problem sets are similar to the conventional tutorial problems that students did at home; however, students are required to submit their solutions to these problems. Continuous assessment encourages students to continuously work as the course progresses and instructors catch students' areas of struggle and provide advice earlier. Moreover, continuous assessment feedback is essential to students' learning because it may help students reflect on their cognitive products about learning objectives. It may result in more control and monitoring of those processes [11]. Hence, students' solutions are evaluated by a tutor to give students continuous feedback that they can use to improve how they implement the "Ten Commandments" in their solutions, as well as improve their problem-solving approaches.

  The weekly problem sets consist of conceptual and free-response questions of varying difficulty levels. Some free-response questions have numerical values for quantities that students can calculate, while others have only variables, limiting students to work with symbolic solutions. The variation in the question types in problem sets and whiteboard tutorial problems is so that students are exposed to different problem-solving experiences to learn from because students' problem-solving abilities may improve to some extent when students are given different types of problems rather than problems of the same type [14, 66, 67]. Furthermore, different problems require different problem-solving approaches, and combinations of commandments are used for different problems.

The problem-solving framework was introduced to the first-year physics curriculum in 2017 and has been ongoing since then. The introductory session is at the start of the year before students are required to do any assessments. During this session, a member of staff presents the framework to the students in PowerPoint format. The presentation slides include an example problem, similar to the type of question they are familiar with from school, to demonstrate how students are expected to implement each commandment in their solutions. Furthermore, the conditions for scoring each commandment are discussed with students, and the presentation slides are made available to students for reference.

Chapter 6

Research Methods and Analysis

To test the effectiveness of the new curriculum structure that includes explicit teaching of problem solving, students' assessment scripts were collected and captured in the first semester of the Physics 1 course in 2019. These data were examined to track whether students were implementing the "Ten Commandments" and subsequently record any evidence of changes to their solutions. Though the intervention did not explicitly target students' attitudes and beliefs about learning physics and problem solving, changes in students' attitudes were measured at the beginning and end of the semester to establish a baseline of their attitudes to problem solving.

Only the scripts of Physics 1 students who gave ethical consent, allowing their scripts and survey responses to be used for the study, were analysed. All students taking Physics 1 follow the same curriculum, i.e., the new structure, and there is no control group for the study. Additionally, we could not use data from years prior to the new structure to match the current results due to ethical clearance constraints. Therefore, with the current results, the changes to students' problem-solving abilities cannot be solely attributed to explicit problem-solving teaching.

6.1 Data collection and Ethics

Because all students taking the Physics 1 course are doing the same curriculum, permission to use students' academic data was required to evaluate the effectiveness of the problem-solving intervention. Ethical permissions for this study was granted by the Rhodes University Science Ethics sub-committee for Human Research, Ethics number SCI12017/002. At the beginning of the semester, students were given a consent form (Appendix 10) to sign, indicating whether they agreed to participate in the study, and the only data for those who agreed were used for analysis. 65 students who took Physics 1 in 2019, 56 gave consent for their data to be used for the study.

Data for this study were collected mainly in the first semester because students are taught by a research team member who understands the importance of scaffolding students and encouraging the use of the framework in lectures, emphasizing the importance of using the problem-solving framework and showing students how to practically apply the commandments while building on the students' conceptual knowledge of Physics 1.

6.1.1 Scoring problem solving

A problem-solving rubric was designed to evaluate how students implemented the commandments in their solutions. The rubric, in Figure 6.1, was initially developed by the researcher in 2017, and later refined to the one in Figure 6.2 to make it easier to delegate the marking in 2019.

In 2019, students' problem-solving scores for assessment tasks were determined using the rubric in Figure 6.2 to demonstrate evidence of problem-solving strategies in student solutions. A problem-solving score is a total mark obtained by the student based on the commandments they applied in their solutions, i.e., the sum of marks obtained for each commandment. Each applicable commandment had a standard maximum allocated mark equal to two points and students are marked using the criteria in Table 6.1.

As part of the delegation process, a marker, who was a postgraduate student and a tutor, liaised with the course lecturer weekly to collect the problem-set scripts, model solutions, and blank printed rubrics (Figure 6.2). The tutor evaluated student solutions for correctness using traditional grading methods, and therefore resulting in the performance mark for the student, and also indicate whether there was evidence of implementing a particular applicable commandment, which constituted the problem-solving feedback. The tutor was asked to tick either **Yes**, **Partly**, or **No** depending on how students used the commandment in their solutions using the criteria in Table 6.1 as a generic guide. Since different combinations of commandments are applicable to different problems, the **N/A** block was included to indicate that a particular commandment was not applicable to solve the problem. Though the tutor was not a research team member, she was coached to ensure that she understood the framework and the criteria for marking and was also given a template rubric with comments and marks allocated for applicable commandments for each problem in the problem set.

Two problems from each weekly problem set were selected and marked by the tutor using the problem-solving rubric; students would receive both performance and problem-solving feedback attached to their scripts, usually before the next problem set was due. Copies of the feedback on rubrics were kept for analysis by the researcher. Students were not told beforehand which problems would be marked and only scripts of the students who attempted to solve the marked problems were analyzed.

The same problem-solving rubric was used to examine evidence of the student's use of the problem-solving framework in tests and the mid-year exam. The tests and exams aim to assess students' understanding and use of the concepts taught in class to solve problems. The course

WPS Marking Schedule						Marks:
Name:				Problem Set No.		
Student Number:				Date:		
Elements	Question No.		Comments	Question No.		Comments
	Marks Allocated	Marks Obtained		Marks Allocated	Marks Obtained	
Diagram(s)						
Variables						
Coordinates						
Physics Principle						
Symmetries						
Prediction of the answer						
Logical Structure						
Symbolic Solution						
Dimensional Analysis						
Answer						
Total:						
General Comments:						

Figure 6.1: Problem-solving rubric used to evaluate students' problem solutions based on the commandments implemented to solve the problem. Students' problem-solving score represents the sum of the scores for each commandment implemented. Furthermore, the comments section is included so that the marker can explain why students received the score they did and write suggestions for improvement. Each score sheet has space for two problems to be scored.

ProblemSolving Marking Schedule

Name:						**Problem Set No.**				**Marks:**
Student Number:						**Date:**				
Elements	**Question No.**					**Question No.**				
	Yes	**Partialy**	**No**	**N/A**	**Comments**	**Yes**	**Partialy**	**No**	**N/A**	**Comments**
Diagram(s)										
Variables										
Coordinates										
Physics Principle										
Symmetries										
Prediction of the answer										
Logical Structure										
Symbolic Solution										
Dimensional Analysis										
Units										
Significant Figures										
Answer										
Total:										
General Comments:										

Figure 6.2: Refined problem-solving rubric used to evaluate students' problem solutions in 2019.

Table 6.1: Criteria for allocating marks for commandments implemented.

Allocated scores for commandments			
Allocated Score	**No = 0**	**Partly =1**	**Yes = 2**
Diagrams	No attempt.	Pictorial representation with substantial information missing	A fully annotated diagram, similar to Figure 5.4, with all the information necessary to the problems included
Variables	No variables defined or listed.	Variable defined incorrectly but used consistently in the solution.	Variables defined and used correctly.
Coordinates	No defined coordinates and direction of vectors not considered in the solution.	No coordinates defined but use a minus sign for vectors in the opposite direction in the solution.	Coordinate system defined as described in Section 5.2.1 and used consistently in the solution.
Physics Principles	Incorrect principle.	Partially correct principle.	Correct principle used.
Symmetries	Student did not explore possible symmetries to solve the problem.	Able to identify applicable symmetries but could not implement in solution.	Appropriate symmetries defined and implemented.
Prediction of the answer		Comment if answer is too big or too small.	Expected answer given before calculation or Correct predictions of dependency of quantities.
Logical structure	-Steps do not follow logically. -wrong answer. - incorrect use of maths operations, i.e, a root of a negative number.	Half solution. Minor maths errors.	Solution easy to follow. Steps follow logically. Correct use of mathematical operation.
Symbolic Solution	Plug-and-Chug.	Symbolic solution but incorrect.	Correct Symbolic solution.
Dimensional Analysis (DA)	Incorrect dimensions.	Evidence of DA but incorrect units at the end.	Expression is dimensionally correct.
Units	Did not get to an answer or No units provided.	Incorrect units.	Correct answer with correct significant figures and units.
Significant figures	Did not get to an answer or Did not consider significant figures.	Partially correct significant figures.	Correct significant figures.
Answer	Did not get to an answer.	Got to an answer but incorrect.	Correct answer.

lecturer assessed students' solutions and graded for the assignment of course marks while the researcher examined students' solutions for problem-solving traits following the same procedure and rubric as the tutor.

Since students were not prompted to use the problem-solving framework in their solutions, they used any problem-solving approach they were comfortable with to solve problems. The course lecturer marked their test and exam solutions, and allocated a performance score to indicate students' understanding based on the course objectives. Any correct solution to test and exam problems was graded regardless of the approach used, and the mark obtained for the tests did not necessarily represent students' problem-solving ability. For example, a student who solved a problem using plug-and-chug and obtained a correct answer would be given the same grade as a student who used the "Ten Commandments" in their solution and also obtained a correct answer. The researcher later separately determined problem-solving scores for tests and exams using copies of the scripts to reveal the differences in students' problem-solving approaches. Students did not receive problem-solving feedback for tests and exams because scoring of student problem solving was usually done after they had received their test feedback.

This set of data obtained from students' assessment tasks was analysed to demonstrate problem solving as described in the following subsections.

6.1.2 Demonstrating whether students were using the framework to solve problems

The problem-solving scores of 1 and 2 indicated evidence of use of a particular commandment, with 1 being a partial attempt made and 2 indicating that the procedure was fully followed (see Table 6.1 for scoring reference). Students with both scores 1 and 2 were combined in a tally by the researcher for each problem and each commandment. This was done in order to determine the number of students who implemented the commandments in their solution over time and also what commandments were used the most by the students. For example, if forty students attempted to solve a marked problem, the number of students who produced diagrams for the problem, and hence followed the first commandment, was determined by combining the number of students who got both scores 1 and 2 for the diagram commandment. The same procedure was used for all commandments and for each of the marked problem.

From this tally, a Sankey diagram, a blank example of which is shown in Fig. 6.3, was generated to show evidence of use of the commandments in solution of five problem sets and two tests in semester 1. A Sankey diagram was chosen as a suitable data representation form to represent how students used the "Ten Commandments" in their solutions to five problem sets and two tests because a Sankey diagram represents a process, where flow lines can combine together or split through their paths on each stage of a process.

A Sankey diagram consists of nodes, i.e, colored blocks representing the variables of the process and the number of columns on the diagram represent different stages in the process. The grey linking lines between the nodes, i.e, links, show the interaction between the nodes. These have been described in detail in the results chapter 8.1.

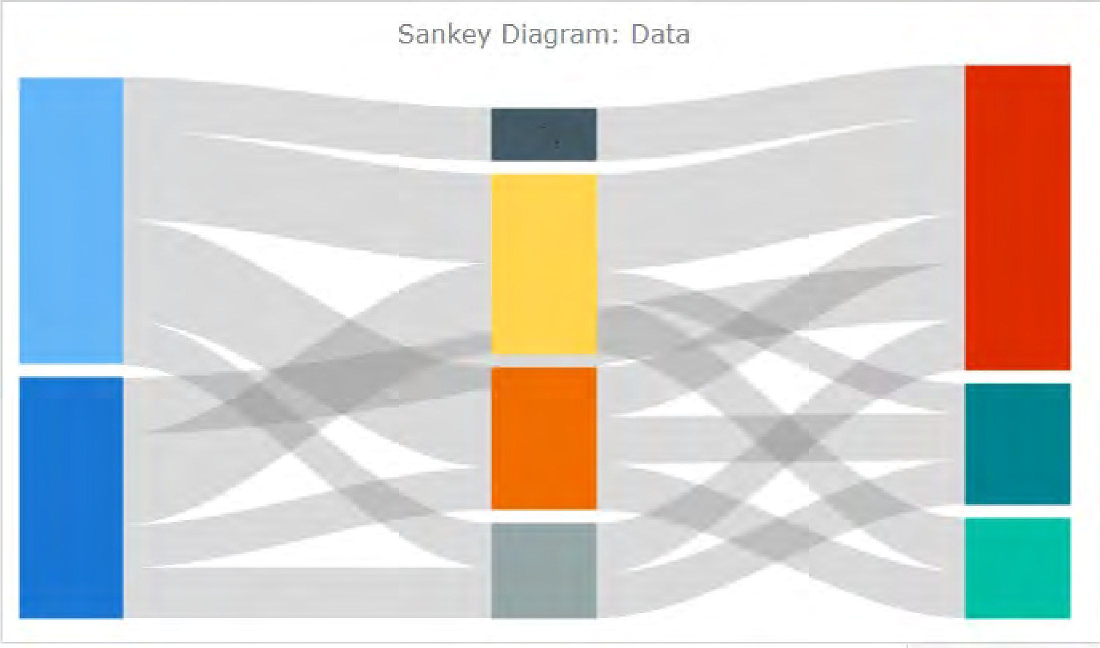

Figure 6.3: An example of a Sankey diagram used to track which commandments where mostly used by the students.

6.1.3 Demonstrating shifts in students' problem-solving approaches

A quantitative analysis of students' problem-solving scores was done to show shifts in students' problem-solving approaches. This analysis assumes that students' problem-solving levels are directly proportional to students' problem-solving scores. Higher problem-solving scores suggested a higher problem-solving ability and students applied many of the applicable commandments more accurately than those with low scores. A plot comparing students' average problem-solving scores at the beginning and end of Semester 1 was produced. Additionally, a comparison of average problem-solving scores end-semester with scores of a test in Semester 2 was made. An analysis of a test in semester 2 was included in order to show whether students continued to use the framework even when not emphasized. A statistical p-test was also performed to test for the significance of the results for this analysis.

6.1.4 Evaluating the relationship between problem-solving ability and performance

Each of the students' assessment tasks was evaluated in two ways. A performance score was allocated to students using traditional grading methods that only evaluated student solutions for correctness and students obtained a problem-solving score using the rubric. A quantitative analysis was done to test for any correlations between students' performance and problem-solving ability.

Problem sets were assigned to students to help them practise using their knowledge and the framework. Generally, homework problems are assumed to help prepare students for formal assessments. A follow-up analysis of the relationship between problem-solving score and performance in test was done to test any relationship between students' scores in problem sets and test to understand the effectiveness of problem sets in helping students prepare for the tests.

6.1.5 Measuring students' internal shifts after being introduced to the new structure

The development of students' problem-solving techniques occurs in stages, and sometimes changes in students' problem-solving approaches do not manifest immediately in their solutions [2]. The first set of changes occur internally, starting with a student recognising the need to adopt newly-taught strategies. With this in mind, students' attitudes and beliefs about learning and solving problems in physics were measured using the Colorado Learning Attitudes about Science Survey (the CLASS) version 3 to show shifts in students' perspectives after a semester of being introduced to the problem-solving framework.

The CLASS is an instrument designed to probe students' attitudes and beliefs about learning physics and problem-solving in physics [68, 39]. The survey consists of 42 statements to which students respond by choosing an option that expresses their thoughts about each statement using a 5-point strongly agree to strongly disagree scale (see Appendix 10). 41 of the CLASS statements are attitudinal statements written as either expert-like statements or as novice-like statements and one statement (statement number 31) is included as a filter statement to test whether students are reading the statements before answering. 26 of the survey statements are grouped into eight validated categories consisting of a combination of 4-8 statements per category. The grouping of the statements is not mutually exclusive in that one statement can be counted in more than one category.

The categories of CLASS are described as follows [69]:

- Real world connection: Seeing the connection between physics and real life.
- Personal interest: Do students feel a personal interest in or connection to physics.
- Sense-making or effort: For me (the student), exerting the effort needed toward sense-making is worthwhile.
- Conceptual understanding: Understanding that physics is coherent and is about making sense, drawing connections, and reasoning, not memorizing or making sense of math.
- Applied conceptual understanding: Understanding and applying a conceptual approach and reasoning in problem solving, not memorizing or following problem-solving recipes.

- Problem-solving categories: No descriptions are provided for the problem-solving categories. Problem Solving:Confidence is a subset of Problem Solving:General. There is some overlap between Problem Solving:Sophistication and Problem Solving:General.
  - Problem Solving:General: Understanding the value of equations in understanding physics and building knowledge structures.
  - Problem Solving:Confidence: Are students confident in solving problems.
  - Problem Solving:Sophistication: Understanding that problem solving is more than just the use of equations, and problem-solving methods are not based on surface features of the problem.

Shifts in students attitudes and beliefs about physics and solving problems in physics were measured by comparing the differences in their responses to the survey at the beginning and end of the first semester of 2019. Responses to the survey from the beginning of the semester were taken before students were introduced to the problem-solving framework or had any physics instruction at university. These are referred to as pre-instruction data. The same survey was given to students in the last week of the semester and these responses are referred to as post-instruction data.

Students' pre- and-post responses are recorded on the supplementary analysis tool provided with the CLASS survey. The analysis tool provides scoring of the data by matching students' responses with responses of experts used in the development, design, and validation process of the survey [68, 69]. For each statement, the analysis tool gives an output of the number of students whose responses agree (favourable), disagree (unfavourable), and neutral with those of the experts and averages per category are also calculated. Lastly, the analysis tool further compares the pre- and-post instruction results and gives the number of students whose responses have shifted towards either agreeing or disagreeing with those of experts at the end of the semester. Favourable shifts are shifts towards expert-like views while unfavourable shifts are shifts towards novice-like beliefs and attitudes.

Not all data captured on the analysis tool are considered. The following conditions are used by the CLASS tool before student data were analysed.

- Statement 31 of the survey is used to check whether students read the statements before responding to the survey. As a result, if a student has not provided a correct response to this statement, his/ her survey responses will not be included in the analysis.
- If students have skipped responses for five or more statements their data will be excluded from the analysis.
- In the case of using CLASS data to understand shifts as a result of instruction, only matched data are considered for analysis. Matched data are when students pre- and-post responses are captured in the same order.

Kiviat (spider) diagrams were generated using average favourable results for each category. Matched pre- and-post-instruction results were plotted to illustrate shifts in students' attitudes and beliefs about physics and solving problems after one semester of physics in 2019. Since pre-instruction CLASS data were also collected in 2017 and 2018, a plot comparing pre-instruction data for 2017, 2018, and 2019 was also generated to gain more insight about students' incoming attitudes and belief. Hence, these data are useful in understanding how previous schooling influences students perspectives and factors contributing to their unpreparedness.

Part III

Evaluating the Solution

A problem-solving intervention aimed at helping physics students develop their problem-solving skills was introduced to the first-year physics curriculum in 2017. Students were taught to solve problems using the " Ten Commandments" problem-solving framework developed by members of the lecturing staff in the Department of Physics and Electronics Department at Rhodes University. The extent to which the problem-solving intervention helped improve students' problem-solving approaches and problem-solving performance was investigated. Copies of assessment scripts and survey responses of 56 students who gave consent to use their data were examined to evaluate the effect of the intervention were collected and analyzed as described in Chapter 6. This part presents and discusses the results of the analysis.

Chapter 7

Students' Attitudes and Beliefs about Physics and Problem Solving

Students' attitudes and beliefs about physics and solving problems in physics were measured using the Colorado Learning Attitudes about Science Survey (the CLASS) to establish the baseline of students' attitudes before implementing the problem-solving framework and measuring shifts at the end of the semester. Instruction influences how students think about a discipline and how they learn and solve problems in the discipline. Students' pre-instruction responses to the survey were to some extent influenced by how they were taught to learn and solve problems in school. As a result, this Chapter compares the results of students' pre-instruction responses for the years 2017, 2018, and 2019 to reveal students' incoming perspectives about physics and solving problems in physics. Additionally, shifts in students' attitudes and beliefs about solving problems in physics after one semester are demonstrated using matched pre-and-post-instruction responses from 2019.

7.1 Incoming Students' Attitudes and Beliefs about Physics and Problem Solving

At the beginning of the year, before any instruction in physics had taken place, students were given the Colorado Learning Attitudes about Science Survey (CLASS) to measure their pre-instruction attitudes and beliefs about problem solving. Their responses to the survey were analyzed as described in Section 6.1.5 and the results of the analysis of pre-instruction results for 2017, 2018, and 2019 are shown in Figure 7.1.

The responses for the three years are similar, with only a $\pm$ 2% difference in students' incoming perspectives about physics and solving problems in physics for all years. This shows that the students who took Physics 1 in 2019 (for which the data was taken) are not markedly different

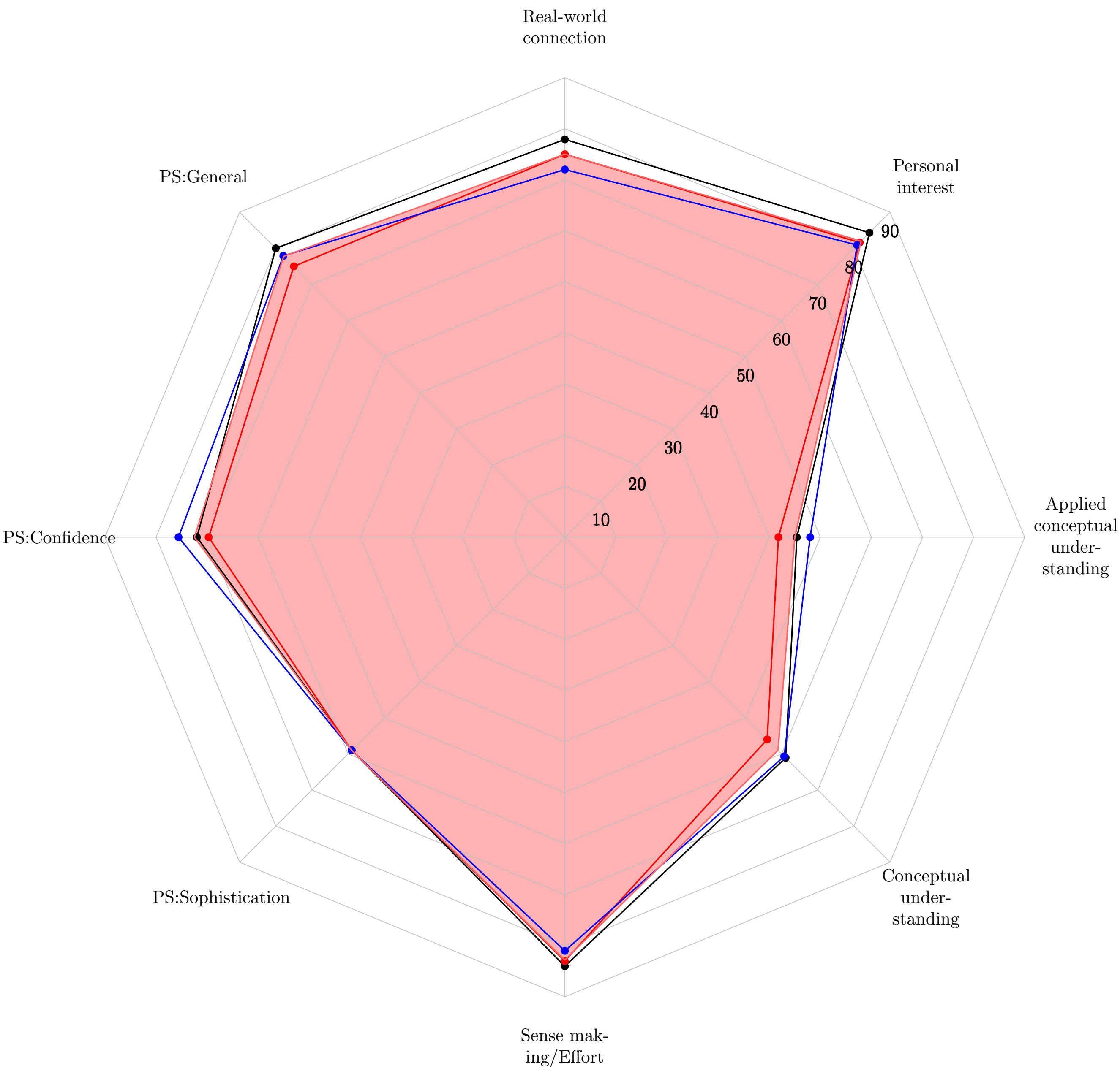

Figure 7.1: Students' incoming perspectives about physics and problem solving (PS) in physics demonstrated using pre-instruction survey responses for the years 2017 (black line), 2018 (red line),and 2019 (blue line). These responses are inclusive of the responses of students who did not take the post-instruction survey. The pink-shaded area in the Figure shows the mean values for each category.

from those in the years immediately before them. The means show the average perspective of students and are used to describe the overall influence previous schooling has on students' attitudes and beliefs about problem-solving in physics i.e, overall incoming attitudes and beliefs about solving problems in physics. The Sense Making/Effort and Personal Interest categories have the highest number (about 82%) of students that agree with experts' views. Conceptual Understanding and Applied Conceptual understanding have the lowest percentages of 59.3 % and 45.1 %, respectively. Applied Conceptual Understanding has the lowest mean percentage for all the years and has the lowest number of students that agree with experts across all categories. The Problem Solving Sophistication category is at the same level (59.1 %) for all years and is the lowest among problem-solving specific categories. Furthermore, a mean of 77.8 % of students agree with expert beliefs about Problem-Solving General and 72% for Problem-Solving Confidence.

Students who take physics at university are often those who enjoyed physical sciences at school. Their felt interest towards physical science, as a result of previous schooling, resulted to their decision to take the Physics 1 course at university. Additionally, their personal interest drives their motivation to continue exerting effort towards making sense for better understanding of physics and solving problems in physics. Hence, many students who took Physics 1 agree with experts in this category.

Though students do agree that understanding physics is about making sense and drawing connections between physics topics, and that reasoning and making sense of the maths is the best way to learn physics, many students feel that conceptual reasoning and qualitative reasoning are not necessary when solving problems. About 74% of students in 2017, 75% in 2018 and 67% in 2019 agree that they solve problems by locating an equation containing variables in the problem and plugging in values. Furthermore, 55% percent of students in 2017, 40 % in 2018 and 53% in 2019 shared the view that problems have to be very similar in situation for them to be solved using the same methods. This is reflected in the relatively low agreement with experts in the PS: Sophistication category. These views both disagree with those of physics expects; however, incoming students are expected to think this way about problem solving because of how they were taught to solve problems at school. The high school final-examination marking guidelines and final-exam-paper memoranda show that students are taught and assessed to solve problems using the plug-and-chug approach (described in Section 2.2). Additionally, the lack of applied conceptual reasoning in using the plug-and-chug approach when solving problems makes students think solving problems in physics does not require qualitative analysis [1]. Furthermore, the use of plug-and-chug resulted in students missing learning opportunities to learn from the problem-solving experiences because their attention was directed towards manipulation of equations rather than identifying the important features of the problem and the solution development process.

Students' dependency on equations to solve problems and thinking problem situations with similar features are solved using the same methods are novice ways of solving problems indicating a low problem-solving sophistication. Additionally, this way of thinking suggest that students come to university with problem-solving schemas which categorise problems based on surface features rather than physical concepts used to solve problems. This is a common trait of students in introductory courses; however, such schemas are deemed inefficient towards solving problem by the physics experts. Nonetheless, students are more confident about solving problems this way and think that they will be able to figure other ways to solve problems when they are stuck.

7.2 Understanding shifts in students' attitudes after being introduced to the problem-solving framework

Students' attitudes and beliefs about physics and solving problems in physics were both measured at the beginning (pre-instruction) and at the end of the semester (post-instruction) in 2019 as described in Section 6.1.5 . Survey responses of 56 students who gave consent for their data to be used for the study were captured for analysis. Because of the data selection criteria (see Section 6.1.5) by the analysis tool, only 26 pre-instruction and 15 post-instruction responses were analyzed in 2019.

To demonstrate shifts in students' attitudes and beliefs about physics and solving problems in physics after one semester of being introduced to the problem-solving framework matched pre-and-post responses from 2019 were used. Figure 7.2 was generated from the responses of the 15 students who met the data selection criteria for both their pre-and-post instruction responses.

More than 70% of students agreed with expert views about Sense making/effort, Personal interest, Problem-Solving: General, and Real-World Connection categories. The Problem-Solving: Sophistication and Applied Conceptual Understanding categories had the lowest number of students agreeing with expert views on statements relating to the categories. Post instruction, the Personal Interest and Real-World Connection categories show the largest favourable shifts, with more than 85% of the students agreeing with experts in these categories. There were overall unfavourable shifts in students' perspectives on statements relating to Problem-Solving: Confidence and Sophistication categories, and the Problem-Solving: General category showed no overall favourable shifts. The largest unfavourable shifts of about 11 percentage points occurred for students in 2019 changing away from having initially favourable perspectives about Applied Conceptual Understanding and Problem-Solving sophistication categories. Lastly, there were small favourable shifts of 2-3 percentage points in Sense Making and Conceptual Understanding categories. Statements contributing to the largest shifts in categories, especially those relating to problem solving, are shown in Table 7.1.

The framework introduced into the first-year physics curriculum aims to help students adopt expert-like problem solving habits. Expert-like problem solving approaches differ from the way in which students learned to solve problems at school. Expert problem solving relies on

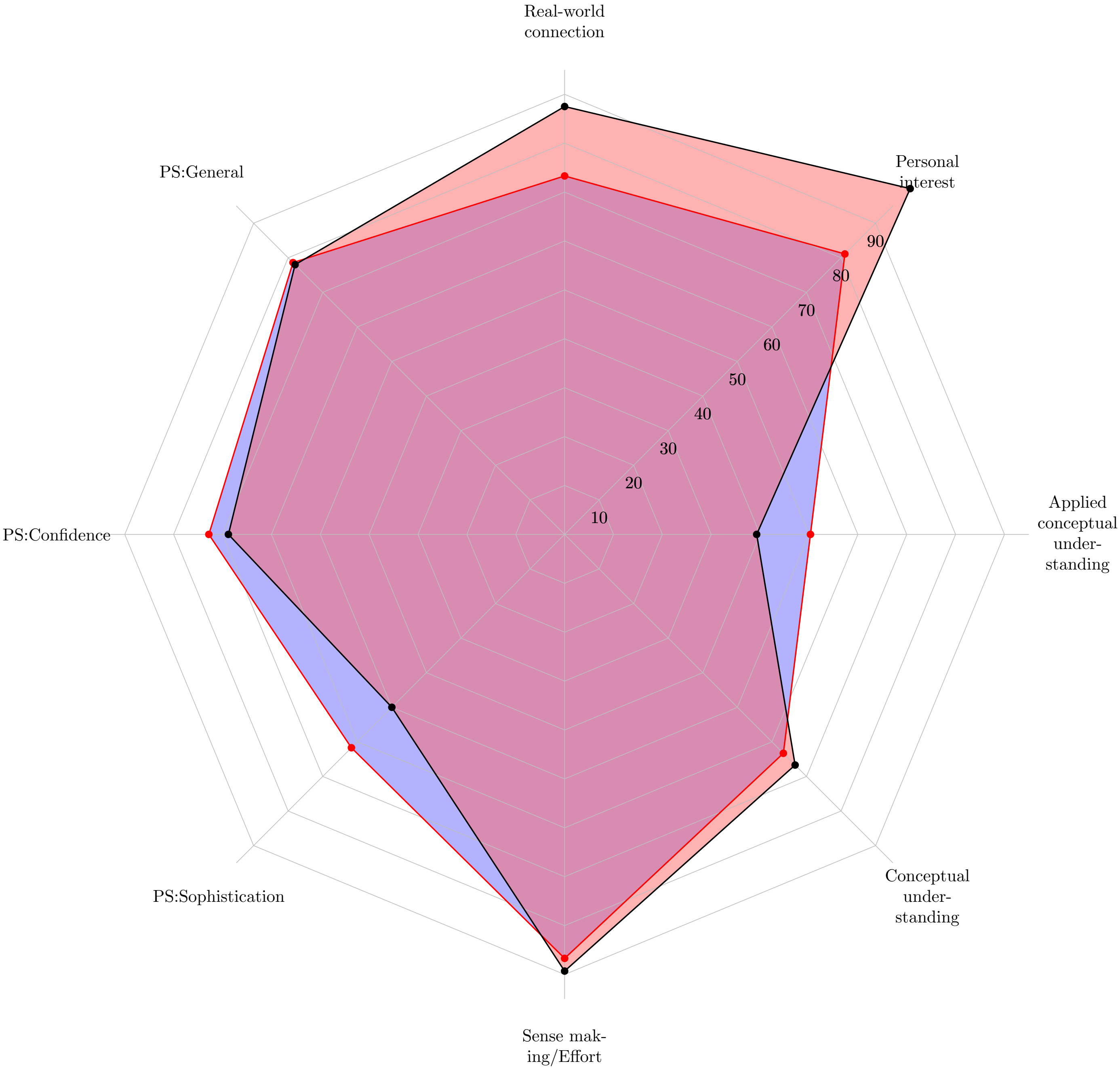

Figure 7.2: A comparison of students' pre (red) and post (black) instruction survey responses for 2019. The light-orange shaded area represents favourable shifts indicating an increase in the number of students who agree with expert perspectives in each category by the end of the semester. The blue-shaded area represents a decrease in the number of students who initially agreed with experts' views at the beginning of the semester then shifted either to disagreeing or being neutral at the end of the semester i.e unfavourable shifts.

the use of physics concepts and qualitative reasoning to develop solutions, meaning that there is less dependency on equations and the ability to apply concepts becomes a requirement. Though personal interest may steer students' motivation towards learning physics and solving problems in physics, this interest alone is not enough to help develop students' problem-solving habits. The process of learning about new ways to solve problems can be quite uncomfortable because some unlearning of old habits has to happen. As a result, students' confidence towards solving problems would probably drop and students will not enjoy solving problems during this time. The survey results by question (Question 25 in Table 7.1) indicate a 13 percentage point unfavourable shifts in the number of the students in 2019 who felt they did not enjoy solving physics problems at the end of the semester. Additionally, there was a 20 percentage point shift away from being confident that they could always figure a way to solve a problem when stuck to thinking that they would need help progressing with their solutions (Question 40 in Table 7.1). Furthermore, several students expressed that they did struggle to navigate the problem space to find solutions, even when they felt like they understood the physics topic they were working on. These responses contributed to the overall negative shifts in students' Problem-Solving: Confidence and Sophistication categories.

Since problem solving is central to physics assessment, being unable to solve problems creates fear of not performing well in physics. So, to save the semester, students would be likely to resort to using problem-solving strategies they were comfortable with and know to be successful. Hence, student solutions show more than 40% of the students in 2019 were found to be using plug-and-chug to solve problems even after a semester of being encouraged to use the framework (see Section 8.5).

On the surface, the results seem to suggest that the problem-solving framework intervention hindered students' development of problem-solving skills. But since there is no control group of students who took the CLASS pre-and-post-instruction survey without experiencing the problem-solving intervention it is impossible to attribute these shifts to the intervention. However, there is a beacon of hope in some positive shifts in students' beliefs, suggesting that with time students' positive problem-solving perspectives may be recovered. More than 84% of students in 2019 agreed with experts that nearly everyone is capable of understanding physics if they work at it. Although many students were using plug-and-chug to solve problems by the end of the semester, 19% of students believed that problem solving is more than locating equations and plugging in values.

Table 7.1: Statements that contributed to large shifts in problem-solving categories

	net shift towards	% point shift	Other categories
Problem Solving :Sophistication			
5. After I study a topic in physics and feel that I understand it, I have difficulty solving problems on the same topic.	Novice	7	Conceptual Understanding, Applied Conceptual Understanding.
21. If I don't remember a particular equation needed to solve a problem on an exam, there's nothing much I can do (legally!) to come up with it.	Expert	30	Conceptual Understanding, Applied Conceptual Understanding.
22. If I want to apply a method used for solving one physics problem to another problem, the problems must involve very similar situations.	Novice	13	
25. I enjoy solving physics problems.	Novice	13	Problem Solving: General
34. I can usually figure out a way to solve physics problems.	Novice	11	PS:General
PS:General			
16. Nearly everyone is capable of understanding physics if they work at it.	Novice	13	Problem Solving: Confidence
40. If I get stuck on a physics problem, there is no chance I'll figure it out on my own.	Novice	20	PS:Sophistication, PS:Confidence. Applied Conceptual Understanding. Sense Making / Effort
42. When studying physics, I relate the important information to what I already know rather than just memorizing it the way it is presented.	Expert	20	Sense Making/Effort
PS:Confidence			
15. If I get stuck on a physics problem on my first try, I usually try to figure out a different way that works.	Expert	20	PS:General
Sense Making / Effort			
23. In doing a physics problem, if my calculation gives a result very different from what I'd expect, I'd trust the calculation rather than going back through the problem.	Expert	12	
24. In physics, it is important for me to make sense out of formulas before I can use them correctly.	Expert	4	
39. When I solve a physics problem, I explicitly think about which physics ideas apply to the problem.	Novice	13	
36. There are times I solve a physics problem more than one way to help my understanding.	Novice	20	
Applied Conceptual Understanding			
8. When I solve a physics problem, I locate an equation that uses the variables given in the problem and plug in the values.	Expert	19	

CHAPTER 8

Evidence of Use of the "Ten Commandments" in Students' Solutions

A problem-solving rubric (Figure 6.2) was used to track evidence of use of the problem-solving strategy by looking at how students implemented the "Ten Commandments" in their solutions. Two Sankey diagrams, in Figure 8.1 and Figure 8.2, were generated using data from students' problem-solving rubrics. The numbers presented in both figures do not include tracking for continuous use of the commandments by students. For example, the number of students who drew a diagram in Problem Set 2 may or may not include students who drew the diagram in Problem Set 1, and tracking of whether students who drew diagrams in Problem Set 1 continued to do so throughout the semester is not included here.

8.1 Reading of a Sankey diagram

The Sankey diagrams below have 3 columns. The first column consists of one node named "all students". The linking lines from the "All student" nodes do not represent absolute numbers, but rather give a visual representation of the relative numbers of students who attempted the problems assessed in each problem set. The thickness of each linking line from this node represents the relative number of students as a percentage of the 56 students who signed the consent form allowing the use of their data for the purposes of the study. Additionally, all students wrote the tests and all attempted the problems assessed for problem solving, so each linking line from "All students", in Figure 8.2, to test nodes represent 100 % of students.

The middle column is the assessment column with each node labeled with a task name. The links from each assessment node to the commandment nodes (in column 3) show the relative number of students who attempted to use the applicable commandments to solve the problems. Again, each link represents a relative percentage of the total number of students who attempted to solve the problem for the task.

The size of each block is determined by the stack of the outgoing links. Though the total number of students is 56 for all assessment tasks, the sizes of the "all student" nodes in Figures 8.1 and 8.2 differ because the nodes have a different number of links going out to the assessment node. There are five links of different sizes in Figure 8.1 and two in Figure 8.2 from the "all students" node, and the size of each node is equivalent to the stack of the links. Similarly, the Problem Set 1 and 4 nodes (see Figure 8.1) have bigger blocks than the other problem sets because these tasks have the most attempts for all of the applicable commandments (i.e, thicker links) even those with more attempts of the problem i.e Problem Set 5. This means that while more students attempted the assessed problems in Problem Set 5, the relatively shorter stack of outgoing links suggest that fewer students used the problem-solving strategy. Additionally, the sizes of commandment nodes are determined by the stack of the incoming links from the different assessment tasks. The size of each commandment block correlates to the overall use of each commandment by the students. For example, the length of the predict/check commandment (see Figure 8.1) is a stack of thin links from Problem Sets 3, 4, and 5 and this commandment has the smallest block of all the commandments, meaning that it was less implemented by the students.

Because problems differ, different sets of commandments apply to different problems. Commandments which do not apply to a particular problem are graded as not applicable (N/A) and all N/A commandments are illustrated by missing links from the assessment node. Additionally, the links to commandments with a total count of attempts equal to zero are also removed from the diagram because the program presents them as thin links which can be interpreted as a small portion of students implementing a commandment. Table 8.1 is a list of applicable commandments which were not used by students in problem sets, and Tables 8.2 and 8.3 list N/A commandments for problem set and test problems, respectively.

8.2 Students' use of the "Ten commandments" in tests and problem sets

Though two problems from each problem set were evaluated using the problem-solving rubric, only the results of one problem per problem set were used for the Sankey diagram in Figure 8.1. The chosen problems had more applicable commandments with more students attempting them. Four of the total problems have numerical values for quantities, while one has only symbols for quantities. Most of the commandments were applicable to the problems and none of the problems required the students to identify and use symmetries. Commandments not applicable to the problem set problems are shown in Figure 8.2.

Students implemented more of the problem set problems as the semester progressed; however, the attempts to implement the commandments in solutions decreased with time, except for Problem Set 4. Problem Set 4 had problems similar to the ones students encountered at school

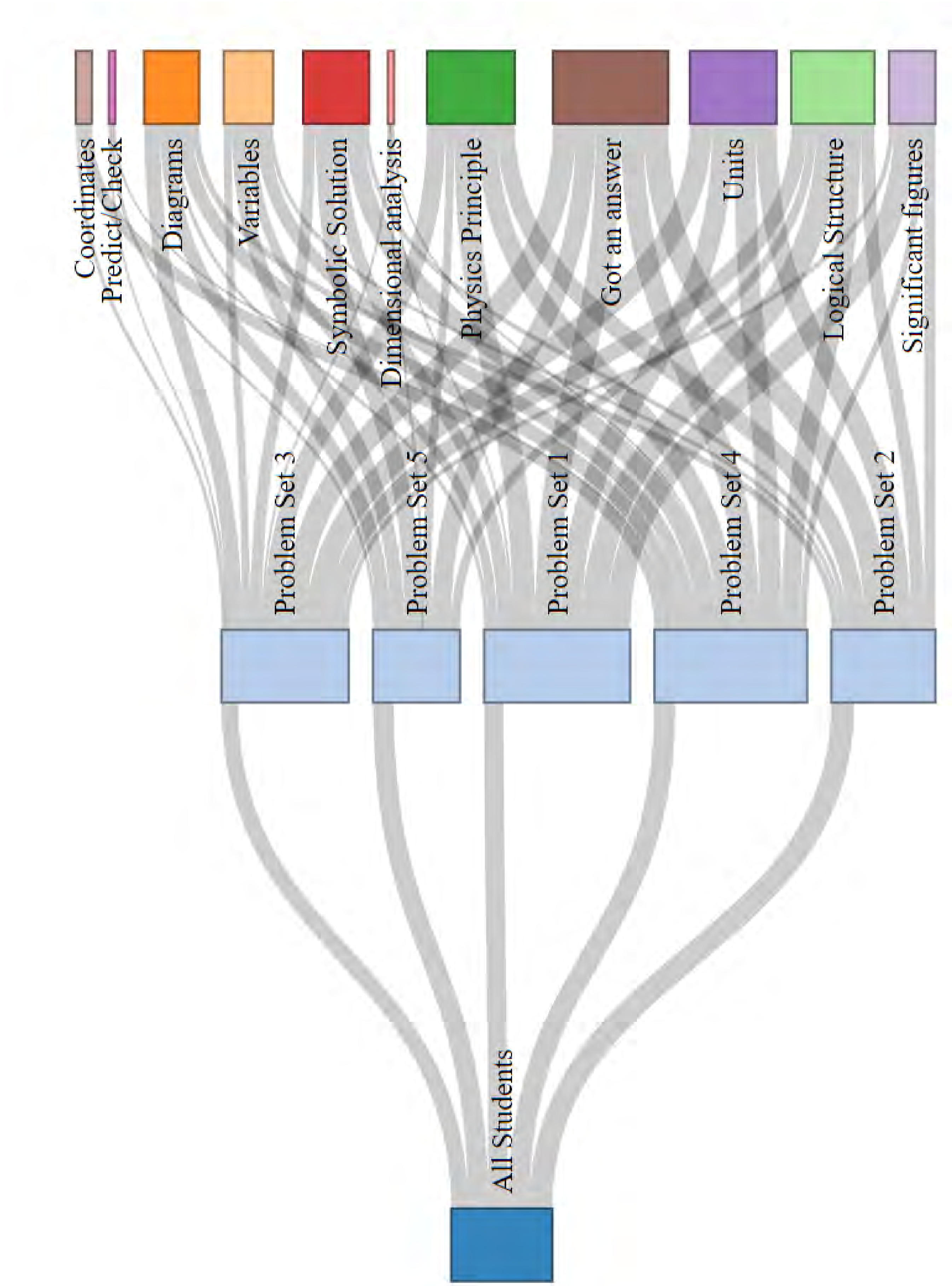

Figure 8.1: Tracking the use of the "Ten Commandments" and evidence of a problem-solving strategy used by students in five problem sets in one semester after being introduced to the problem-solving framework.

on the same topic (Forces and Newton's Laws) and many students were able to implement most of the applicable commandments correctly. Many students were able to determine physics principles applicable to the assigned problems and were able to get to an answer to most of the problems, and to determine the units of quantities they were solving for. However, the linking lines from the assessments to the logical structure commandment suggests that as the semester progressed students were producing less structured solutions to the problems, especially for Problem Set 5 where only a few students were able to determine and apply the principle correctly resulting in a corresponding lack of logically structured solutions.

Table 8.1: Missing links for commandments with zero attempts in assessments.

Problem Set 1	**Problem Set 2**
Predict or Check	Predict or Check
	Dimensional Analysis

Table 8.2: Commandments that were considered as not applicable in problem sets.

Problem Set 1	**Problem Set 2**	**Problem Set 3**	**Problem Set 4**	**Problem Set 5**
Coordinates	Coordinates			Coordinates
Symmetries	Symmetries	Symmetries	Symmetries	Symmetries
				Units and Significant figures

The increasing thickness of the linking lines to the Variables, Diagrams, and Symbolic Solution commandments suggests that more students were shifting towards implementing them in their solutions as the semester progressed. This could be because students are familiar with the use of variables and diagrams and these commandments were emphasized in lectures. However, students' solutions show that they used these commandments more for challenging problems rather than straightforward problems. The Dimensional Analysis and Coordinates commandment were among the least used commandments and the Prediction commandment was the most disregarded commandment amongst all. This could be because these are the least familiar commandments and perhaps students do not see how they can help.

8.3 How students were using the commandments in tests

Figure 8.2 shows how students used the "Ten Commandments" in two tests written in the first semester. One problem per test was analysed and was chosen for the applicability of a wider range of commandments. As with the problem sets, neither of the test problems required students to identify and implement symmetries to solve them. Neither problem required students to include units and significant figures (see Table 8.3 below), because they are problems which required students to derive an expression for a quantity. For Test 2, students were explicitly prompted to draw a graph and use the information from the graph to derive an expression. Although students were not prompted to produce a diagram in Test 3, an external diagram would be beneficial to solving the problem because it contained many elements that could not be held in memory at the same time. The problem included vectors, meaning that a student would have to remember their directions. Also, the problem involves more than one object with before-and-after details included. So, if a student attempted to work with a mental representation to solve the problem, some of these details would be missed.

Table 8.3: Commandments considered as not applicable in Test 2 and 3.

Test 2	**Test 3**
Coordinates	Symmetries
Predict / Check	Units and Significant Figures
Symmetries	
Units and Significant Figures	

Students implemented more of the commandments they used in school than the newly-taught ones. They could identify the applicable physics principle to solve the problems because each assessment was related to one specific topic; implementing this commandment therefore, became a mere task of choosing an equation to solve the problem, creating opportunities to use the plug-and-chug approach they used at school and contributing to the losing battle against plug-and-chug [64]. Furthermore, students' solutions show that many solved problems using plug-and-chug and struggled to solve problems requiring qualitative analysis and deriving expressions for quantities.

In summary, students produced diagrams and solved problems symbolically mostly for problems that explicitly required them to do so. Prompting, whether explicit or implicit, makes students not appreciate the importance of the tasks. Because there is always a reward associated with the task students are likely to do it for the reward rather than for learning gains [27]. Additionally, students often opt to work with mental representations of problems and do not get to a correct answer due to mathematical errors, mistakes when substituting values and mistakes when implementing a coordinate system for the problem. Most of their mathematical errors relate to forgetting to change signs during manipulation and including signs for vectors in different directions. These errors result from memory overload and not checking their solutions after solving a problem. Additionally, they rarely checked if their solutions were dimensionally correct because they could always recall the units for the quantities since most of the quantities were in the problems from school. Students did not attempt to implement the predict or check commandment because they did not understand what the commandment required of them.

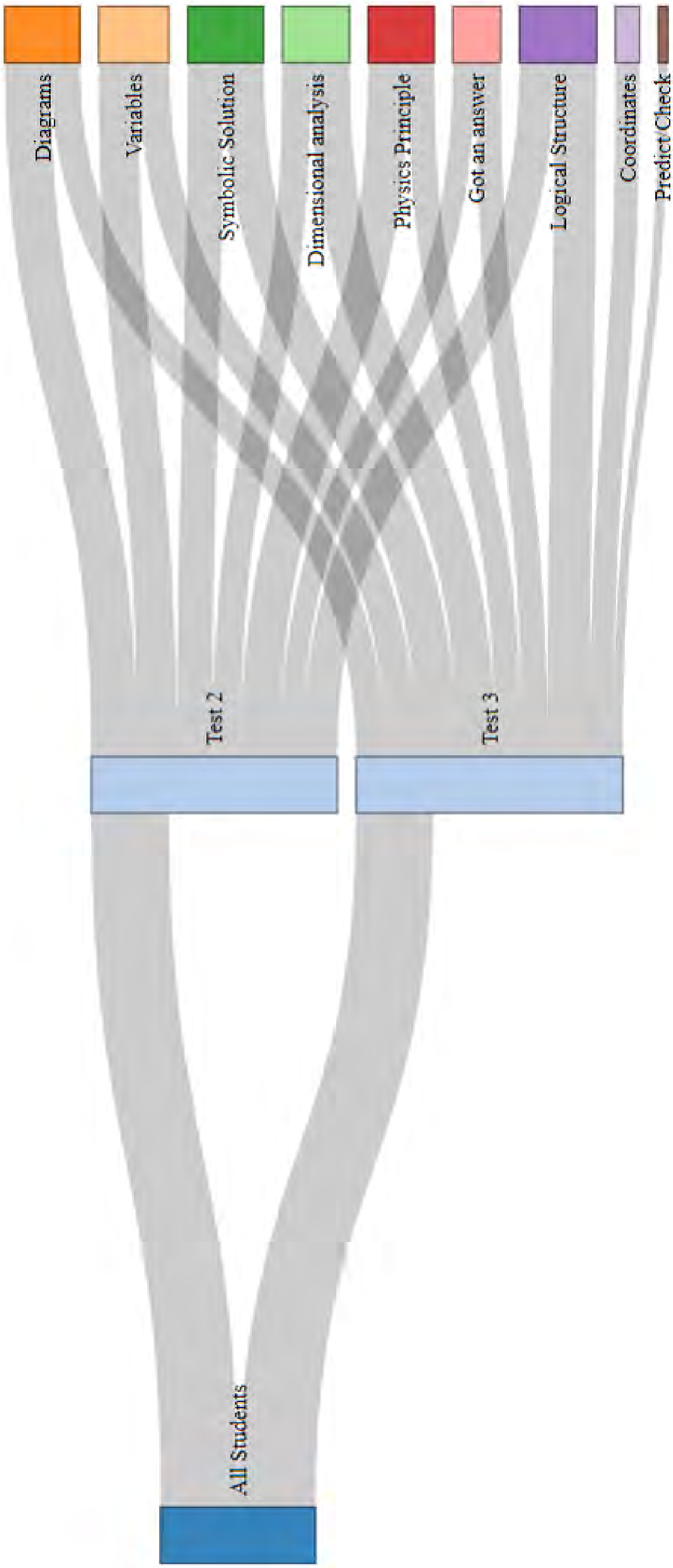

Figure 8.2: Students' problem-solving traits in test problems.

8.4 Demonstrating shifts in students' problem-solving approaches

Students' problem-solving scores indicate whether students are implementing the "Ten Commandments" in their solutions to problems. Higher problem-solving scores also suggest that students are implementing most applicable commandments accurately in their solutions. Plots comparing students' problem-solving scores at the beginning of and later in the semester were generated to show shifts in students' problem-solving scores after they were introduced to the problem-solving framework. Moreover, their average scores from later in semester one were compared to the scores for a test written mid-semester two. Students' problem-solving data were collected during these times because they were taught by a member of the research team during the observed period of semester one and by the researcher in semester two.

8.4.1 Comparing students' problem-solving levels at early and late in Semester 1

Figure 8.3 and 8.4 are plots comparing students' early and late problem-solving scores. Figure 8.3 compares students' average problem-solving scores for Problem Set 1 (early) and Problem Set 5 (late) and Figure 8.4 compares students' average problem-solving scores at the beginning (early) and mid-semester 1 (late). Early problem-solving scores are obtained within the first month of being introduced to the problem-solving framework. The early problem-solving score is the average of the score for Test 2 and the average scores for Problem Sets 1 and 2. The late problem-solving score is the average of problem-solving scores for Test 3 and the averages of Problem Set 4 and 5. The statistical analysis output of the data represented in both figures is summarized in Table 8.4.

The diagonal straight line in both figures is included to represent students whose scores remained unchanged in the first semester. The vertical and horizontal lines in the plots are means (in Table 8.4) for early and late problem-solving scores, respectively.

Table 8.4: The means and significance level of the result in Figures 8.3, 8.4, and 8.5.

Measures	**Means**	**t-statistic**	**Significance**
Figure 8.3	x = 32.62, y = 26.36	1.52	0.1289
Figure 8.4	x = 30.05, y = 37.35	-0.64	0.525
Figure 8.5	x = 39.82, y = 60.26	-4.89	6.549e-6

The mean of students' problem-solving scores for problem sets in Figure 8.3 is lower, by a difference of 6.26 %, at the end of the semester than at the beginning. Additionally, there are more students with data points below the diagonal line in Figure 8.3, meaning most students had higher problem-solving scores for Problem Set 1 than Problem Set 5. The higher problem-solving scores for Problem Set 1 than Problem Set 5 suggest that students attempted

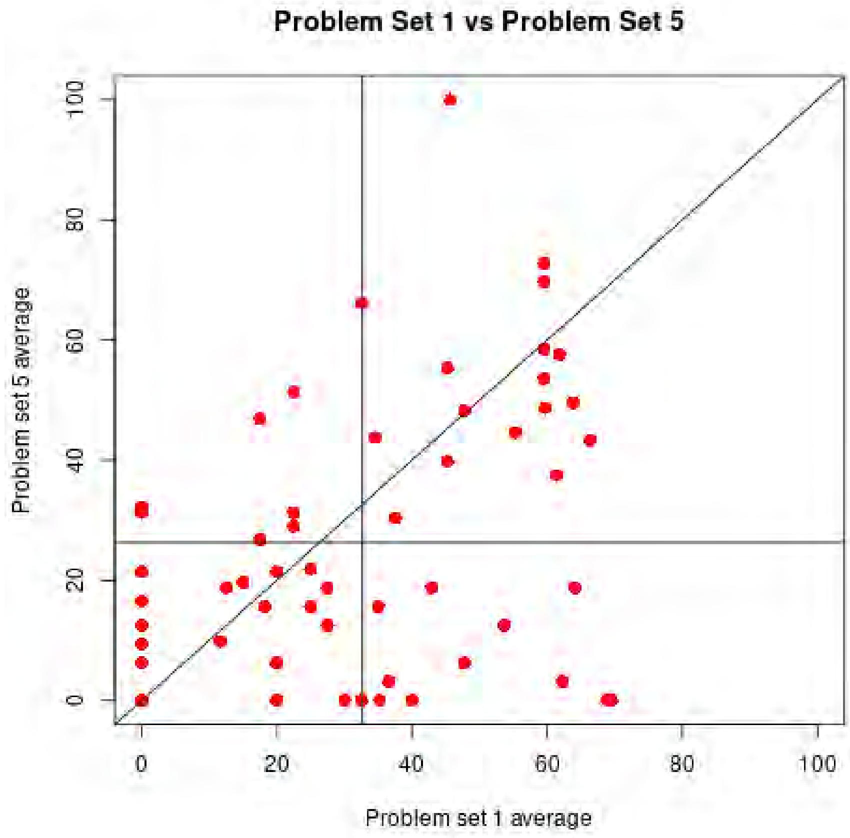

Figure 8.3: Shifts in students' problem-solving scores in Problem Set 1 and Problem Set 5.

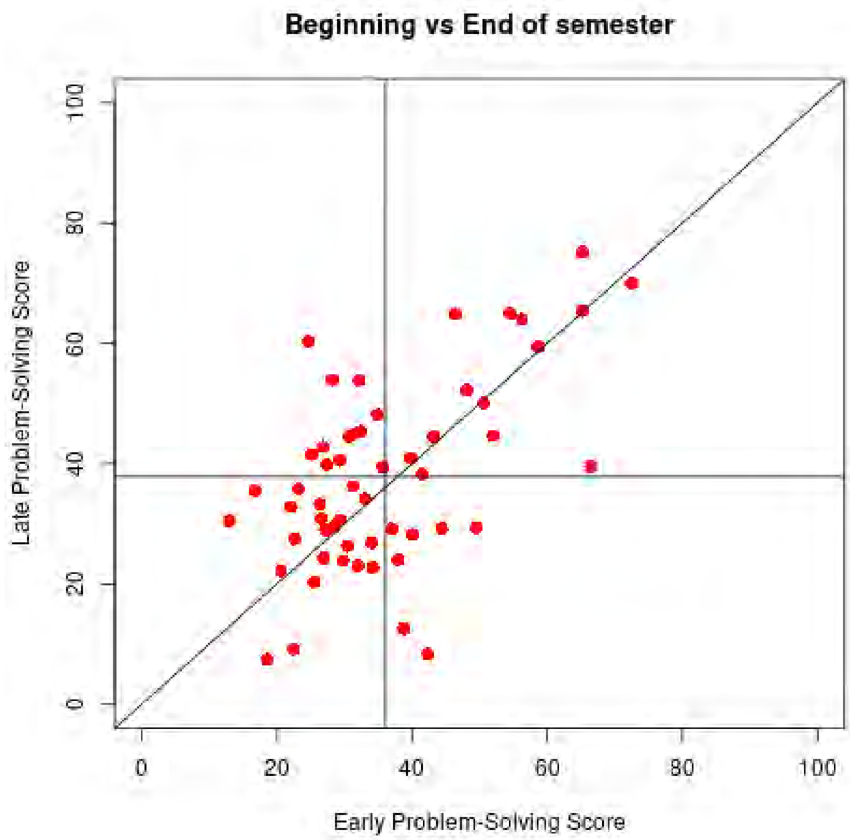

Figure 8.4: Comparing the students' problem solving scores on tasks at the beginning (Early) and in middle of the semester (Late).

to implement more of the applicable commandments in Problem Set 1 than Problem Set 5 because the framework had just been introduced to them before they were given Problem Set 1. These results are consistent with the results reported in Section 8.2.

Figure 8.4 shows a relatively even split between students with data points above and below the constant line (i.e. the diagonal line) showing that similar numbers of students improved and deteriorated in problem-solving scores. Additionally, the data points close to the constant line suggest students' average problem-solving scores remained fairly constant for several students over the semester. The mean of students' average problem-solving scores in Figure 8.4 show a small positive shift (7.3 %), moving towards using the "Ten Commandments" to solve problems.

Though students were attempting to implement the "Ten Commandments" in their solutions to assessments, they still demonstrated poor problem-solving skills in the first semester of 2019. The overall the mean problems-solving scores of the data in the above Figures are less that 50%, which is considered a below average level of problem-solving performance.

8.4.2 Comparing students' problem solving late in semester 1 and semester 2

Figure 8.5 compares shifts in students' problem-solving approaches late in Semester 1 and halfway through Semester 2, in an attempt to further evaluate whether students continued to use the "Ten Commandments" in their solutions to problems after the first semester of 2019 when the framework was no longer freshly introduced. Also, this was done to investigate any long-term effects of the framework on students' problem-solving approaches. Students' late average problem-solving scores from Figure 8.4 were compared with students' problem-solving scores of one test written in the middle of the second semester. The data used to generate Figure 8.5 relate only to the students who took physics in both semesters of 2019 and had given consent for their data to be used for the study (47 students).

The mean score mid-second semester is higher, by 20.26%, than the mean at the end of first semester. Many students obtained higher problem-solving scores for the test considered than the overall scores obtained at the end of first semester. These may be positive results indicating the potential long-term impact of the framework on students' problem-solving approaches. However, these results may also be mitigated by the fact that it is generally students with higher first semester marks that continue to the second semester.

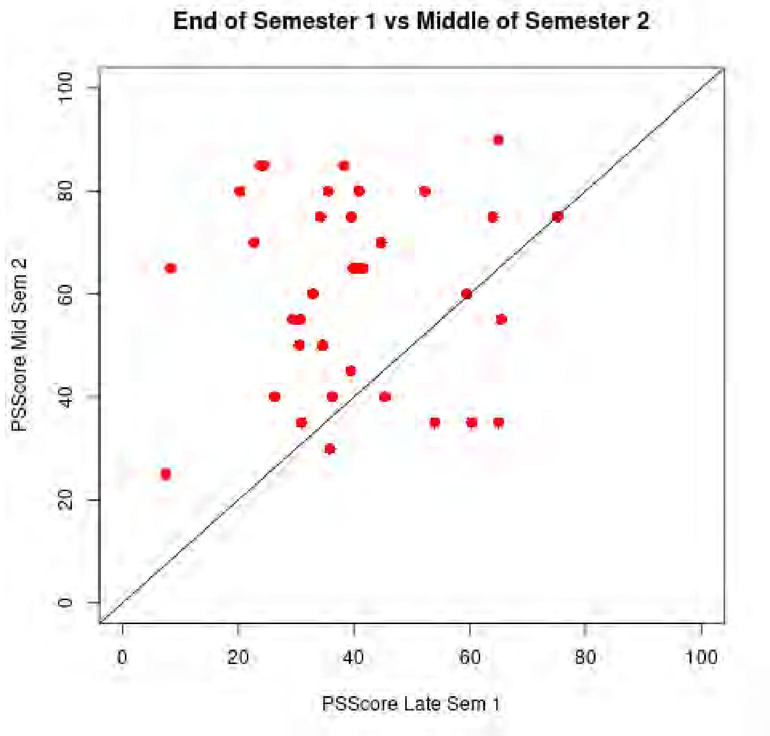

Figure 8.5: Comparing students' problem-solving scores (PPScore) late in Semester 1 with mid-Semester 2.

8.5 Understanding students' problem-solving approaches used in semester 2: The analysis of Electrostatics test question

Of the 56 students in the first semester who gave consent to using their data, 47 continued to do physics in second semester. Students' solutions to a test written in the second semester were analyzed to inspect whether students continued to use the "Ten Commandments" to solve problems even when the use of the framework is not emphasized.

The analyzed test question required students to calculate the distance between q_1 and the point **P**, where **P** indicates the point where the electric field the net electric field generated by both charges (q_1 and q_2) is zero. For this question, a skeleton diagram shown in Figure 8.6 for the problem was included, however, students were not prompted to produce diagrams or add information to the given diagram. Additionally, this question had numerical values given for quantities and students were free to use any approach they were comfortable with to solve the problem. The diagram score is rated based on the amount of detail students included on the provided diagram and those who had a diagram similar to the one shown in Figure 8.7 below were given the maximum diagram score equal to 3. Scores of 2 and 1 were allocated according to missing information on the diagram. A diagram score equal to zero means there was no evidence of an attempt to either draw a diagram or add extra information on the provided skeleton diagram.

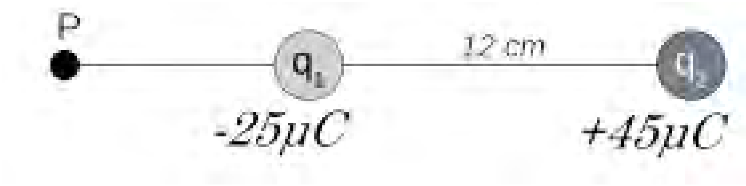

Figure 8.6: Two point charges, $q_1 = -25$ μC and $q_2 = +45$ μC, separated by a distance $d = 12$ cm along the x-axis.

Students solved for the distance by either using the plug-and-chug approach or by first finding the symbolic solution with or without a diagram. Students were considered to have used the plug-and-chug approach when they substituted numbers early in their solutions without evidence of first finding the symbolic expression of x. An exception for substituting 12 cm instead of using the variable d (or any variable) for the distance between q_1 and q_2 was made for the symbolic solution of the problem.

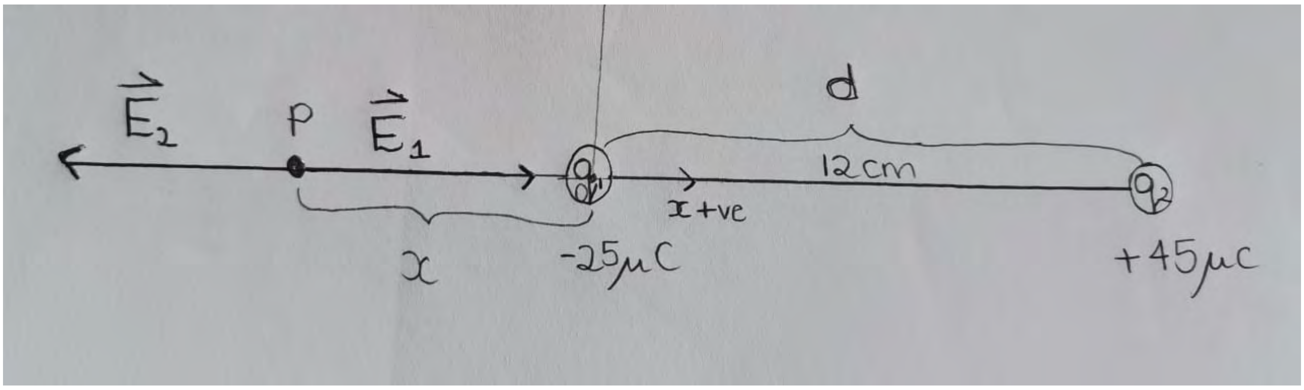

Figure 8.7: A physical diagram of two charges q_1 and q_2 separated by a distance $d = 12$ cm along the x-axis. The position of q_1 is taken as the 0 cm point with an arrow to the right indicating the positive x-direction ($x + ve$).The distance between point **P** and q_1 is defined by the variable x. The electric fields generated by each charge at point **P** are labeled as $\overrightarrow{E_1}$ and $\overrightarrow{E_2}$, respectively, and their directions are shown using the arrows along the x-axis.

Students' solutions showed two ways in which this particular problem was solved. Both solutions worked with the magnitudes of the fields so that x and d are scalar-distances. One way is by manipulating the expressions of $\overrightarrow{E}$ leading to a quadratic expression and the use of the quadratic equation to solve for the distance x (see the first block below). This approach results in two values of x (-0.05 m and 0.351 m) and students had to decide on the actual value of x for the answer. Because the distance is a scalar and thus cannot be negative, the correct distance between **P** and q_1 is 35.1 cm.

$$E_1 = E_2$$

$$\frac{k_e q_1}{x^2} = \frac{k_e q_2}{(x+d)^2}$$

expanding $(x+d)^2$ leading to

$$k_e q_1(x^2 + 2xd + d^2) = k_e q_2 x^2$$

$$(q_1 - q_2)x^2 + 2xdq_1 + d^2 q_1 = 0$$

then use the quadratic equation

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

with $a = (q_1 - q_2)$, $b = 2dq_1$ and $c = d^2 q_1$

The second option is to manipulate the expression as shown below, leading directly to one value of x.

$$E_1 = E_2$$

$$\frac{k_e q_1}{x^2} = \frac{k_e q_2}{(x+d)^2}$$

$$x = \frac{d}{(\sqrt{\frac{q_2}{q_1}} - 1)}$$

The first approach is longer than the second, and is the most used by those students. However, students who used this approach had more mathematical errors compared to the second one. Students' solutions were assessed with the problem-solving rubric to identify the problem-solving approach used by students to solve the problem. Their solutions where categorised according to the problem-solving approach they used (plug-and-chug or symbolic solution), according their diagram scores, and whether they were able to solve the problem, as shown in Table 8.5. The 'Got to an Answer commandment' in the rubric counts for all students who got to an answer even if it was incorrect. Because of this, this analysis further categorised according to their answers, i.e. correct answer or incorrect answer. This was done to identify which problem-solving approach used by the students was more successful of the 47.

All students except for one used a correct physics principle for the problem. Thirty-two students got to an answer and of these 14 got a correct answer. Furthermore, students who got to an answer often included correct units for it. Solutions of the students who did not get to an answer had partial solutions, showing that they got stuck in their solution attempts due to incorrect application of mathematical operations during manipulations of either variables or numbers (plug-and-chug). Additionally, other students had complicated their solutions due to mismatches of directions of the vectors and confusion of variables mid-solution because they used the same variable to represent distances for both charges. The majority of the students (78%) added some information to the provided skeleton diagram, meaning that they did implement the 'Diagram and Variables commandments' in their solutions. Only three

Table 8.5: The evidence of a problem-solving strategy used by students in the second semester when the problem-solving approach was not emphasized. Students solved for x (the distance between $\mathbf{P}$ and q_1) by either using the plug-and-chug approach or by first finding the symbolic solution expression for x. Some students' solutions included the diagram while others did not. Students' errors were identified for each problem-solving approach. The number of students in each block is included in brackets.

		Diag Score	Solved		Not Solved
			Correct Answer	Incorrect Answer	
Plug-and-Chug	No Diagram	0	Direction of $\overrightarrow{E}$ and and algebraic error resulted in correct answer. (1)	Bad maths (1)	Variables mismatch, bad mathematics. (2)
	Diagram	1	Bad mathematics but looked back and fixed the error (1)	Direction of different E and the sign of charges, Bad mathematics, did not include μ when substituting numbers, calculator mistake, confused the directions. (9)	Distance mismatch, direction of $\overrightarrow{E}$ and the sign of charges. (3)
		2		Calculator mistake, coordinate system, an incorrect value of x, bad physics and bad mathematics, memory overload. (3)	Bad start and recovered with mid solution. (2)
		3		Incorrect physics principle and confused variables. (1)	Distance misrepresentation, algebraic error. (1)
Symbolic Solution	No Diagram	0	(1)	Direction of $\overrightarrow{E}$ resulted in bad mathematics. (1)	
	Diagram	1	(7)	Direction of $\overrightarrow{E}$ and the sign of charges, misrepresentations of distances and bad maths (4)	Direction of $\overrightarrow{E}$ and the sign of charges, and bad mathematics. (2)
		2	(1)	Bad mathematics (2)	Bad mathematics, misrepresentation of distances. (2)
		3	(3)		

students, produced a diagram similar to the one in Figure 8.7 and got correct answers using the symbolic solution approach with no errors in their solutions. It is to be expected for students who do not produce diagrams when solving problems to make errors such as confusing the distances between **P** and the two charges and the directions of the electric fields $\overrightarrow{E}$ generated by the charges. These errors are often said to result from students having to hold a lot of information in working memory (i.e. memory overload). Students are often encouraged to produce external representations of problems to organise information and avoid these errors [17]. However, students' solutions show that errors related to mismatch of directions and variables are common even to students who have external diagrams with their solutions. If students checked their solutions after they finished solving the problem or looked back at their diagrams such errors could be corrected. Students' diagrams for this problem had a coordinate system and variables included. However, their solutions show that most students do not look back to their diagrams to check their solution or even use their diagrams to generate solutions. Only one student showed evidence of looking back to check her solution. Her initial solution had a mathematical error and this student cancelled the first attempt and produced a second attempt without the error and got a correct answer. Not using provided diagrams to develop solutions may be a long-term effect of being prompted to draw diagrams at school and students were annotating their diagrams in whiteboard tutorials, because they were advised by the tutors that "having a diagram will get you more marks even when there is an error in your calculation", so it would seem that they do this without using the diagram afterwards.

Even after a semester of encouraging students to solve symbolically and substitute the numbers once they have obtained the expression of the variable they were solving for, slightly over 50 % of students used the plug-and-chug approach for finding the value of x. The results in Table 8.5 suggest that the high mean of students' problem-solving scores is partly a result of being able to apply a correct physics principle and implement partially correct commandments to problem solutions rather than drawing of and using a correct diagram and the related commandments (Variables and Coordinates).

CHAPTER 9

Evaluating the Effect of Problem-Solving in Students' Performance in Physics Assessment Tasks

The scripts of students' assessment tasks were evaluated in two ways; using traditional grading methods and the problem-solving rubric, Section 6.1.1. Traditional grading methods only evaluated students' solutions for correct application of concepts taught in class without focus on the problem-solving approach used and students were given a performance mark. On the other hand, the problem-solving rubric evaluated the use of the "Ten Commandments" in students' solutions and students were given a problem-solving score. The following sections attempt to investigate the relationship between students' problem-solving ability and their performance in assessment tasks.

9.1 Investigating the relationship between students' problem-solving score and performance in assessment tasks

For each problem set, two questions were evaluated using the problem-solving rubric and the problem-solving score was determined by adding the marks obtained for each implemented applicable commandment (see Section 6.1.1). The tutor also allocated the performance mark. Students' tests were marked by the lecturer and copies of the tests were later independently assessed by the researcher using the problem-solving rubric. The students' performance mark in test is the mark allocated by the lecturer for a question and the problem-solving scores are calculated in the same way as for the problem sets. The average problem-solving score (in %)

and average performance (also in %) were calculated for each problem set.

Figure 9.1 is a scatter plot comparing the relationship between students' average problem-solving scores and average performance in Problem Sets (1-5). Figure 9.2 is a similar plot generated with the test data. A linear regression analysis was generated for all the problem sets and similarly for the test data. The summary of the results is shown in Tables 9.1 and 9.2, respectively.

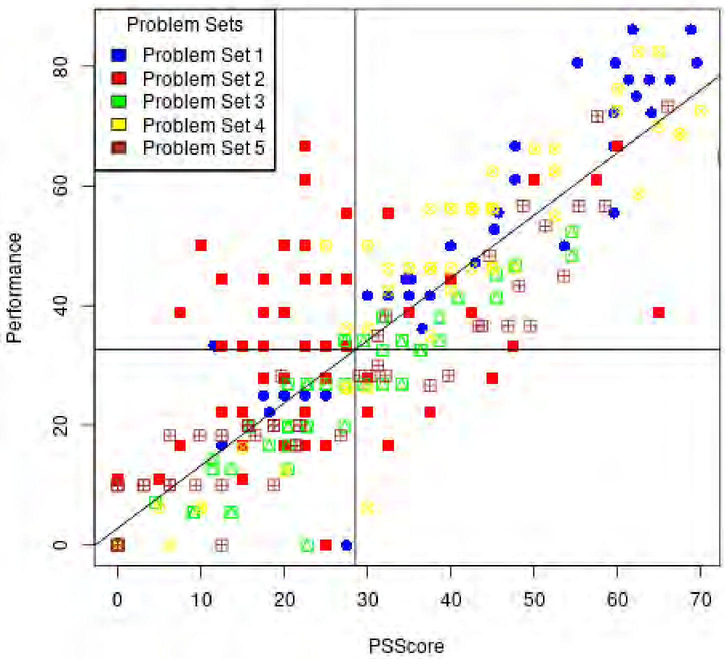

Figure 9.1: The relationship between students' problem-solving score (PSScore) and performance in problem sets. The vertical and horizontal lines on the plots represent the means of the respective data sets.

Table 9.1: Regression output for Problem Set data in Figure 9.1

Problem set regression output		R-squared = 0.806		
Coefficients	Estimate	Std. Error	t-value	p-value
Intercept	2.8	1.0	2.729	0.0067
PSScore (gradient)	1.046	0.030	35	<2e-16

Most of the data points in Figure 9.1 follow the trend of the regression line except for most data points in Problem Set 2. Statistical analysis of the problem-set data shows that for every 1% increase in problem-solving score in problem sets, students performance increases by 1.046 ± 0.030 % (shown by the gradient estimate in Table 9.1). The p-value (p-value $= 2 \times 10^{-16}$) provide statistical evidence of significance of the positive linear relationship between students' problem-solving scores and their performance in problem sets. Additionally, the statistical analysis suggest that this relationship is true for about 80% (R-squared = 0.806) of the data. It is likely that students' average performance marks for Problem Set 2 are higher than their problem-solving score because Problem Set 2 is based on kinematics concepts. Students could solve problems in Problem Set 2 without needing to implement the commandments because they had solved a wide range of similar problems at school.

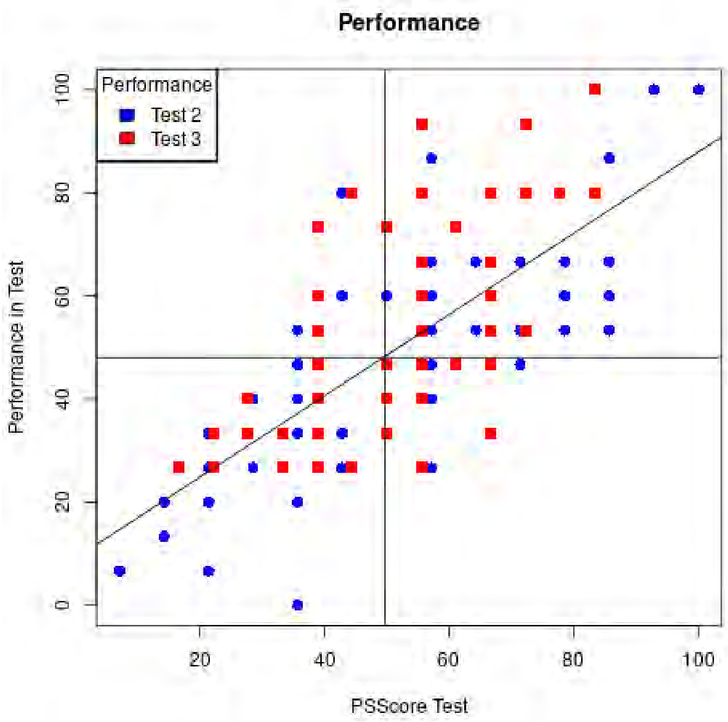

Figure 9.2: The relationship between students' problem-solving score (PSScore) and performance in tests.

Table 9.2: Regression output for the test data in Figure 9.2

Problem set Regression output		R-squared = 0.533		
Coefficients	Estimate	Std. Error	t-value	p-value
Intercept	9.1	3.8	2.3859	0.0019
PSScore	0.789	0.072	11.245	<2e-16

About 50 % (R-squared = 0.533) of the data in Figure 9.2 follow a 1 to 0.788±0.071 % relationship between problem-solving score and the performance in tests. The mean values for both data sets are below the widely accepted minimum pass average of 50%, suggesting that, on average, students' performance on assessments is poor. Students performed better in tests than they did on homework problems. Having to adapt to using the new problem-solving framework to solve problems may be one of the factors contributed to students' poor performance, especially for homework problems because problem sets were explicitly evaluated using the problem-solving rubric. However, students' poor performance cannot be entirely attributed to this. There are additional factors such as having to adjust to new ways of teaching and learning as well as a new environment, that should also have an effect on their performance.

9.2 The relationship between the problem set and test scores

In general, students are given homework problems in the form of problem sets because instructors believe that more homework problems would help prepare students for the formal assessments such as tests and exams. Figures 9.3 and 9.4 were generated to try to understand the relationship between problem-solving scores in tests and problem sets, as well as the relationship between performance in tests and problem sets, respectively. Understanding these relationships is important to understand whether the problem sets are indeed helpful in preparing students for tests and helping students improve their problem-solving abilities. The green diagonal dotted lines in Figures 9.3 and 9.4 represents students whose scores are equal for both assessments tasks. A linear fit line is also included in both the Figures. Regression analysis was performed to provide statistical evidence of the relationship between the variables although it is clear from the large scattering of points that there is no obvious linear relationship.

Figure 9.3 shows the relationship between the problem-solving score in problem sets and the problem-solving score in tests. In the figure, Test 2 is plotted against Problem Set 3 and Test 3 is plotted versus Problem Set 4 since they covered the same concepts. Most data points for Test 2 lie above the green-dotted line, suggesting that students' problem-solving scores in Test 2 were higher than the problem-solving scores in Problem set 3. Test 3 result shows a contradictory result to Test 2. Most students obtained higher problem-solving scores in the problem set than in the test. The statistical analysis of the data presented in Figure 9.3 shows a very weak positive correlation (correlation coefficient = 0.25) between the variables in Figure 9.3 and this relationship only describes 6% of the data. Thus, there is not enough statistical evidence to conclude that there is a relationship between problem-solving scores in tests and problem sets.
Similar trends are seen in Figure 9.4 as are shown in Figure 9.3 for the relationship between the performances in tests and problem sets. The correlation coefficient between the performance scores for the tasks is also a very weak positive of 0.3. Again, not indicating a linear relationship between students' performance in tests and problem sets. These results appear to suggest that giving students more homework problems to supplement learning does not necessarily prepare them for tests. Although other factors could be coming to play, such as the topic covered or the current time pressure of the semester. Different scaffolding strategies, such as concept tests or in class discussions that require students to explain the relationship between concepts and explain natural phenomena could be implemented in order to ensure that students understand the content before they are allowed to solve problems on their own. These results also suggest the importance of aligning homework problems given as problem sets with the final assessment tasks. Since the lecturer concerned claims that she believes alignment between the tasks was indeed present, these results may also indicate difficulties that students have in applying their conceptual knowledge in unseen situations- during test conditions. Without further investigation, it is impossible to identify the dominant factors contributing to these results.

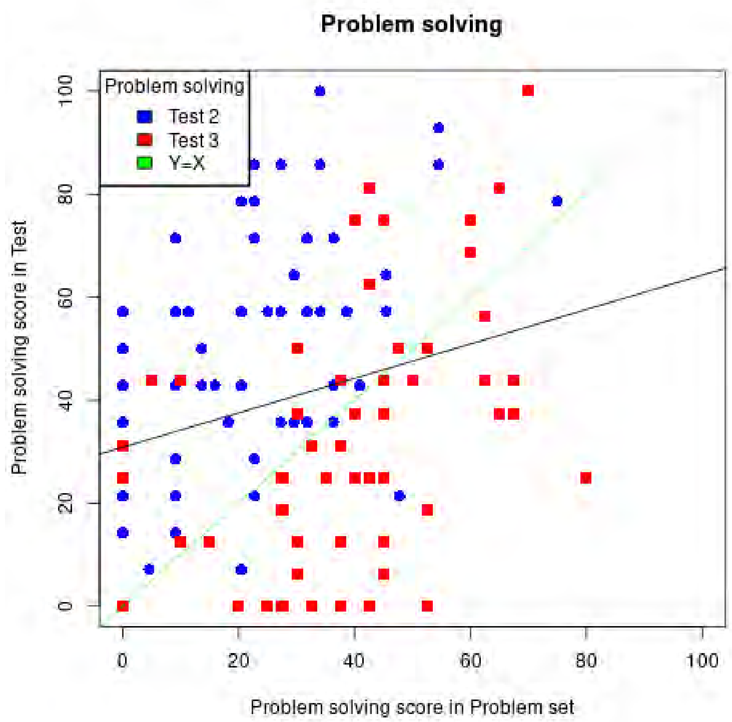

Figure 9.3: The relationship between students' problem-solving score in problem set and problem-solving score in test.

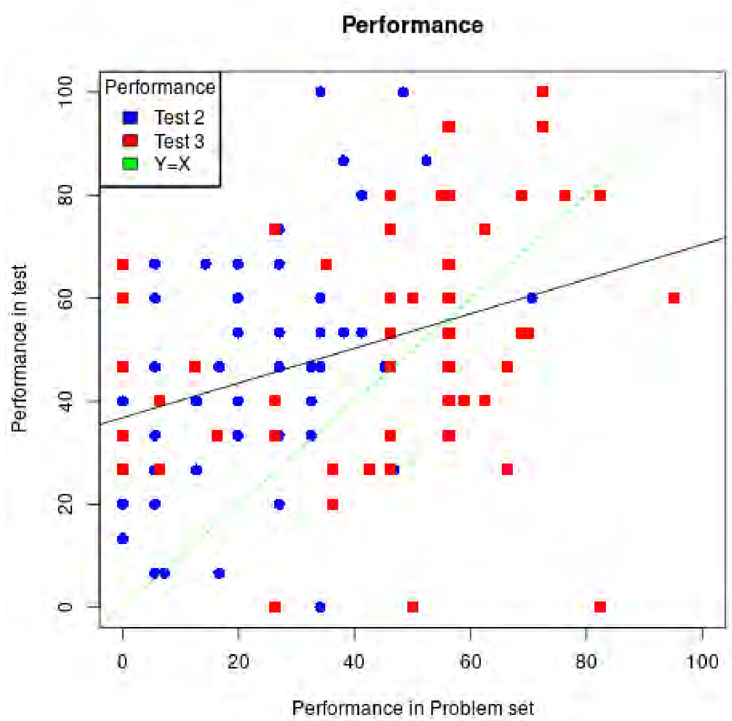

Figure 9.4: The relationship between students' performance in problem set and performance in tests.

CHAPTER 10

Conclusion

Due to the centrality of problem solving in the teaching and learning of physics and the importance of problem solving in the job market, a decision to explicitly teach problem solving at in the Department of Physics and Electronics at Rhodes University was made. A structured problem-solving framework was developed and implemented into the first-year physics curriculum from 2017 and onwards. The problem-solving framework aims to help students shift from using plug-and-chug approaches towards using conceptual-based problem-solving approaches guided by the "Ten Commandments" of physics problem solving. The extent to which students adopted the framework was investigated. Students' solutions to formal physics assessments, which are tests and problem sets, were examined to note any changes in their problem-solving approaches as well as to track how students were adopting the framework in the first semester of the year. Furthermore, changes in students' attitudes and beliefs about physics and solving problems in physics were measured to evaluate the extent to which the framework influenced their internal beliefs.

After one semester of being introduced to the problem-solving framework, students' incoming attitudes and beliefs about physics and solving problems in physics showed unfavourable shifts in their problem-solving confidence and sophistication as well as applied conceptual understanding at the end of the semester. Tracking of students' solutions showed that students were attempting to implement the developed "Ten Commandments" of physics problem solving in their solutions to assessment problems. However, they implemented more of the ones which they were familiar with from school than the newly taught problem-solving commandments such as using Diagrams, Coordinate systems, Symbolic Solution, Dimensional Analysis, Predict/Check, and Significant Figures. In addition, students tended to implement the new commandments for problems that explicitly required them to do so. Additionally, their solutions show that most students are using the plug-and-chug approach to solve problems and demonstrated overall poor problem-solving performance, with means of less than 50% for all assessment tasks. Lastly, students' solutions also showed that they need to work on applying mathematics operations correctly to solve the problem because using mathematics skills incorrectly is a contributing factor to not being able to get to an answer to the problem.

Statistical analysis shows a positive correlation between students' performance in formative assessment tasks and their problem-solving scores for assessments. However, different scaffolding strategies, such as tasks that focus on a specific problem-solving skill rather than requiring students to use the newly taught skills at once (as it is in problem sets) need to be implemented to help students learn to solve problems and prepare students. In spite of these seemingly less than encouraging results, the general feeling of the lecturer teaching the problem-solving framework is that having the framework to use as an explicit teaching tool is more useful than not. As evidenced by the declining use if the problem-solving framework over the semester, it is important for lecturers to continuously emphasise its use, instead of assuming that students will continue to use the framework after first being introduced to it. It is also disappointing that few, if any, of the other lecturers in the department emphasise the "Ten Commandments" problem-solving framework and this could be a contributing factor for students' not continuing to use it in other modules.

In the light of the outcomes of the study, the first-year whiteboard tutorials were being reviewed again and adjusted to focus on explicitly developing problem-solving skills based on the "Ten Commandments". The lecturer has also revised the solutions to problem sets and tests to indicate where different commandments have been used, in order to more explicitly model the continuous use of the framework.

The impact of the above mentioned changes is yet to be investigated. Another fruitful topic for further study would be to research the longer-term effects of teaching problem-solving framework by investigating how students who have continued with physics to second year, third year, and honours now perceive the usefulness of the problem-solving framework.

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Ethics Consent form

The ethics consent form given to students taking Physics 1 at the beginning of the year to sign indicating their willingness to participate in the study.

Informed Consent Form

Project: Assessing Problem Solving Interventions in Physics 1.
Data: Marking of Assessments (tutorials, tests, exams).

This year we are trying a new approach to help first year students improve their problem solving skills. A Physics Masters student is doing a research project to assess how well it is working. We are also planning to publish this research in a journal. **If she is to use any data collected from you, we need your permission!**

The data from this study will be used for this MSc project, for research purposes and will also feed into Rhodes University's curriculum review project, from all of which we hope to publish research.

All the data collected in this study will be used anonymously in any resulting publications (thesis, journal articles or reports).

Participation in this study is voluntary. Participants may withdraw consent at any time.

This study will involve the introduction of a problem-solving framework. All the participants' tutorials, tests and exams will be marked according to this framework and their progress in using it will be recorded. They will receive feedback about their problem-solving progress from the tutorials and tests.

You have agreed to be involved in the marking of the assessments.

Are you willing for the researchers to use data (mark allocations, comments, feedback to students) from your marking of the assessments (tutorials / tests / exams)?

Yes / No

Name: ______________________________

Student/Staff number: __________________

Signature: ___________________________

Date: _______________________________

CLASS Survey

The Colorado Learning Attitudes about Science survey administered pre- and post-instruction.

CLASS

(Colorado Learning Attitudes about Science Survey)

Name: ___________________________________ **Last 6 digits of your Student ID #:** _______

Introduction

Here are a number of statements that may or may not describe your beliefs about learning physics. You are asked to rate each statement by circling a number between 1 and 5 where the numbers mean the following:

1. Strongly Disagree
2. Disagree
3. Neutral
4. Agree
5. Strongly Agree

Choose one of the above five choices that best expresses your feeling about the statement. If you don't understand a statement, leave it blank. If you understand, but have no strong opinion, choose 3.

Survey

1. A significant problem in learning physics is being able to memorize all the information I need to know.

Strongly Disagree	1 2 3 4 5	Strongly Agree

2. When I am solving a physics problem, I try to decide what would be a reasonable value for the answer.

Strongly Disagree	1 2 3 4 5	Strongly Agree

3. I think about the physics I experience in everyday life.

Strongly Disagree	1 2 3 4 5	Strongly Agree

4. It is useful for me to do lots and lots of problems when learning physics.

Strongly Disagree	1 2 3 4 5	Strongly Agree

5. After I study a topic in physics and feel that I understand it, I have difficulty solving problems on the same topic.

Strongly Disagree	1 2 3 4 5	Strongly Agree

6. Knowledge in physics consists of many disconnected topics.

Strongly Disagree	1 2 3 4 5	Strongly Agree

7. As physicists learn more, most physics ideas we use today are likely to be proven wrong.

Strongly Disagree	1 2 3 4 5	Strongly Agree

8. When I solve a physics problem, I locate an equation that uses the variables given in the problem and plug in the values.

Strongly Disagree	1 2 3 4 5	Strongly Agree

9. I find that reading the text in detail is a good way for me to learn physics.

Strongly Disagree	1 2 3 4 5	Strongly Agree

10. There is usually only one correct approach to solving a physics problem.

Strongly Disagree	1 2 3 4 5	Strongly Agree

11. I am not satisfied until I understand why something works the way it does.

Strongly Disagree	1 2 3 4 5	Strongly Agree

12. I cannot learn physics if the teacher does not explain things well in class.

Strongly Disagree	1 2 3 4 5	Strongly Agree

13. I do not expect physics equations to help my understanding of the ideas; they are just for doing calculations.

Strongly Disagree	1 2 3 4 5	Strongly Agree

14. I study physics to learn knowledge that will be useful in my life outside of school.

Strongly Disagree	1 2 3 4 5	Strongly Agree

15. If I get stuck on a physics problem my first try, I usually try to figure out a different way that works.

Strongly Disagree	1 2 3 4 5	Strongly Agree

16. Nearly everyone is capable of understanding physics if they work at it.

Strongly Disagree	1 2 3 4 5	Strongly Agree

17. Understanding physics basically means being able to recall something you've read or been shown.

Strongly Disagree	1 2 3 4 5	Strongly Agree

18. There could be two different correct values to a physics problem if I use two different approaches.

Strongly Disagree	1 2 3 4 5	Strongly Agree

19. To understand physics I discuss it with friends and other students.

Strongly Disagree	1 2 3 4 5	Strongly Agree

20. I do not spend more than five minutes stuck on a physics problem before giving up or seeking help from someone else.

Strongly Disagree	1 2 3 4 5	Strongly Agree

21. If I don't remember a particular equation needed to solve a problem on an exam, there's nothing much I can do (legally!) to come up with it.

Strongly Disagree	1 2 3 4 5	Strongly Agree

22. If I want to apply a method used for solving one physics problem to another problem, the problems must involve very similar situations.

Strongly Disagree	1 2 3 4 5	Strongly Agree

23. In doing a physics problem, if my calculation gives a result very different from what I'd expect, I'd trust the calculation rather than going back through the problem.

Strongly Disagree	1 2 3 4 5	Strongly Agree

24. In physics, it is important for me to make sense out of formulas before I can use them correctly.

Strongly Disagree	1 2 3 4 5	Strongly Agree

25. I enjoy solving physics problems.

Strongly Disagree	1 2 3 4 5	Strongly Agree

26. In physics, mathematical formulas express meaningful relationships among measurable quantities.

Strongly Disagree	1 2 3 4 5	Strongly Agree

27. It is important for the government to approve new scientific ideas before they can be widely accepted.

Strongly Disagree	1 2 3 4 5	Strongly Agree

28. Learning physics changes my ideas about how the world works.

Strongly Disagree	1 2 3 4 5	Strongly Agree

29. To learn physics, I only need to memorize solutions to sample problems.

Strongly Disagree	1 2 3 4 5	Strongly Agree

30. Reasoning skills used to understand physics can be helpful to me in my everyday life.

Strongly Disagree	1 2 3 4 5	Strongly Agree

31. We use this statement to discard the survey of people who are not reading the questions. Please select agree-option 4 (not strongly agree) for this question to preserve your answers.

Strongly Disagree	1 2 3 4 5	Strongly Agree

32. Spending a lot of time understanding where formulas come from is a waste of time.

Strongly Disagree	1 2 3 4 5	Strongly Agree

33. I find carefully analyzing only a few problems in detail is a good way for me to learn physics.

Strongly Disagree	1 2 3 4 5	Strongly Agree

34. I can usually figure out a way to solve physics problems.

Strongly Disagree	1 2 3 4 5	Strongly Agree

35. The subject of physics has little relation to what I experience in the real world.

Strongly Disagree	1 2 3 4 5	Strongly Agree

36. There are times I solve a physics problem more than one way to help my understanding.

Strongly Disagree	1 2 3 4 5	Strongly Agree

37. To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed.

Strongly Disagree	1 2 3 4 5	Strongly Agree

38. It is possible to explain physics ideas without mathematical formulas.

Strongly Disagree	1 2 3 4 5	Strongly Agree

39. When I solve a physics problem, I explicitly think about which physics ideas apply to the problem.

Strongly Disagree	1 2 3 4 5	Strongly Agree

40. If I get stuck on a physics problem, there is no chance I'll figure it out on my own.

Strongly Disagree	1 2 3 4 5	Strongly Agree

41. It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.

Strongly Disagree	1 2 3 4 5	Strongly Agree

42. When studying physics, I relate the important information to what I already know rather than just memorizing it the way it is presented.

Strongly Disagree	1 2 3 4 5	Strongly Agree