What is logical deduction, in relation to physics, and how can students improve in this?

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Abstract

This research was done in the context of the increasing emphasis on thinking in education and the contention by many researchers that improvement in thinking leads to improvement in learning. The other context is the difficulty of physics as a subject at high school and the constant search for better methods of teaching the subject. The objective was to investigate the suitability of logic education as a method to improve students understanding of physics.

The current state of physics and thinking education was explored in the Literature Review. This included an analysis of methods aimed at improving student performance in physics, improving thinking and improving performance in physics *by* improving the thinking that occurs in this subject. Consequently, logical deduction in physics was deemed an area with the potential to support such improvement. As well, the process of logical deduction was found to need clarification.

The nature of logical deduction was, therefore, explored using a philosophical method. The first outcome of this was that the process usually thought of as ‘logical deduction’ was reconceptualised as ‘deductive inferring’. This was to better reflect its nature as a thinking process. Wittgenstein’s critique of solitary rule-following was then applied to the processes of deductive and inductive inferring, and they were problematised accordingly. Consequently, a more accurate delineation of these processes was given as *deductive-like* and *inductive-like* inferring.

To assess the suitability of logic education for physics education, the thinking involved in physics problem-solving was investigated empirically using a think-aloud method. It was found that deductive-like inferring played a key role in this thinking. For instance, it was implicated in moving from the information given in a question, alongside assumed knowledge, towards an answer.

The results strongly suggested that logical deduction should be an element in a suite of thinking skills explicitly taught to high school physics students, and that more emphasis should be placed on logic and thinking more generally in education. The results of these analyses also motivate further research in this area and suggestions for these were made.

Declaration

I hereby declare that this thesis is my original work towards the Master of Education Degree at the University of Melbourne. Due acknowledgement has been made in the text to all other materials used and I attest that the word count is fewer than the maximum allowed.

Russell McKenzie

Contents

1. Introduction

1.1 Rationale for this research

The rationale for this research is the need to improve the thinking of high school students in physics and, consequently, enable their greater understanding of the subject. Though it was not always so, the link between student thinking and learning is now much better understood (see Reif, 2008). Consequently, there is a growing body of research committed to the improvement of thinking in education, such as Harvard's Project Zero (for example, Ritchhart et al., 2011) and the broader critical thinking movement (for example, Fisher, 2001).

Why physics thinking? I have been a high school physics teacher for twenty-eight years and have observed the difficulty some students have in understanding the subject. I have also come to appreciate that good teachers teach thinking skills as well as subject-based content. With a background in philosophy, I started to believe that a significant part of the thinking in physics was logical thinking – a form of thinking that is not exclusive to physics. I saw the possibility that some of the thinking processes of physics could be distilled into syllogisms (explained below) and when I discovered Project Zero's program of thinking improvement, it occurred to me that, if students improved in their *general* thinking (including logical thinking) then they would, consequently, improve in their *physics* thinking.

The logical thinking that I believed was particularly relevant to physics was *logical deduction.* Consequently, my research question is: What is logical deduction, in relation to physics, and how can students improve in this? So, this research attempts to clarify the nature of logical deduction generally and then investigate how it is, or could be, applied to physics thinking.

1.2 Logical deduction

Logical thinking is normally thought of as the drawing of conclusions from other statements, called premises, in a systematic way. Another term that is used is *deductive thinking*, or, simply, deduction. A famous example of a deduction is as follows:

All humans are mortal, and, since Socrates was a human, he was also mortal.

The conclusion (that Socrates was mortal) could be established from the truth of the premises (All humans are mortal and Socrates was a human).

Deductive thinking is often contrasted with *inductive thinking*. Theoretically, there is no room for doubt in deductions – if the premises are true then the conclusion must be true. In inductive thinking, conversely, the conclusion is thought to be only *probably* true when the premises are true – there is a possibility of the conclusion being false.

A deduction where the conclusion must follow from the premises is said to be *valid.* To assist with the analysis of deductions, they are often abstracted to a formulaic series of statements called *syllogisms*.

The above deduction has the same form as the following syllogism:

> *P1: All A's are B*
> *<u>P2: x is an A</u>*
> *C: Therefore, x is a B*

Where 'P1' refers to the first premise, 'P2' refers to the second premise, 'C' refers to the conclusion and the line under the premises signifies the relation 'therefore'. Note how letters have replaced the objects or properties mentioned in the deduction – this is to better see whether it matches one of the known valid deductions and, in this case, it does. Compare this deduction with the following:

> *Some diodes are LEDs, and some diodes are made from germanium. Therefore, some LEDs are made from germanium.*

This 'deduction' is invalid, as it follows the pattern:

> *P1: Some P's are Q's*
> *<u>P2: Some P's are R's</u>*
> *C: Some Q's are R's*

It is invalid because it is possible that none of the Q's that are P's are also R's. That is, it *is* possible for the premises to be true and yet the conclusion be false.

If a series of thinking manoeuvres, when abstracted using the method shown, matches one of the valid syllogisms, then it is thought to constitute a logical deduction. The ability to differentiate valid deductions from non-valid ones appears to be valuable because it gives a means of judging whether a person is thinking deductively.

1.3 Physics and logic

I wondered whether physics education may benefit from a focus on logic when I was teaching both physics and philosophy in the Victorian Certificate of Education. I became aware of parallels between the thinking that I was expecting of students in physics and that which I was expecting of students in philosophy.

For example, consider that reasoning that may occur in answering the following question:

> *A box is being pulled across a horizontal floor, with a horizontal force of 30 newtons, at a constant velocity of 4 metres per second. Find the magnitude of the force of friction acting on the object.*

This is clearly a physics question, involving physics concepts such as ‘force’, ‘velocity’ and ‘friction’. However, to answer it a student needs to combine the information given in the question with their knowledge of physics principles.

The first part of one’s reasoning in answering this question could be:

> *P1: All objects travelling with a constant velocity or remaining stationary, have zero net force acting on them. (Newton’s first law)*
> <u>*P2: This box is travelling at a constant velocity.*</u>
> *C: The net force on the box is zero. (This conclusion then allows you to infer that the force of friction must have the same magnitude as the ‘horizontal force’.)*

The first premise is a statement of a universal principle, which is required prior knowledge, while the second premise is contained in the question. The conclusion appears to be reached using logical deduction – a process that is not specific to physics. That is, it is possible that someone who does not have the required physics knowledge, but who was presented with these premises, would be able to reach the correct, logical conclusion.

I wondered whether success in physics depended not only on one's knowledge and understanding of physics principles, but also on the ability to think *logically*. For instance, in an examination, the student has only their knowledge, understanding and thinking ability to rely on. If the use of logic guarantees a correct answer, it would be very useful for students to learn it. It also seems likely that it would find many applications, since much of physics involves universal laws, and many questions in physics involve an instantiation of such laws.

This thesis considers the role of deduction in studying physics and whether it *should* be used and taught explicitly as a valuable thinking tool.

1.4 Logic and schools

There is widespread agreement about the benefits of students learning logical thinking and reasoning. For instance, Baserer (2020) says: 'people with logical thinking and reasoning abilities can solve complex problems. Yet these skills are not often explicitly taught in school' (p. 177). Reif (2008) suggests that the use of deductive thinking can reduce the amount of information a student needs to learn in mathematics and sciences, since they can use this knowledge to 'reliably infer a much larger amount of knowledge' (p. 111).

In the state of Victoria, Australia, logical thinking is construed as an important skill – one to be encouraged in lower years of schooling. It is included in the curriculum for year levels from Preparatory to Ten in the Critical and Creative Thinking Capability, where it is part of the Reasoning 'Strand' (VCAA, 2015). The other two strands are 'Questioning and Possibilities' and 'Meta-cognition'. One of the aims of the Capability is that students develop 'skills and learning dispositions that support logical, strategic, flexible and adventurous thinking' and part of the Grades Five and Six curriculum is for students to 'examine the difference between valid and sound arguments and between inductive and deductive reasoning, and their degrees of certainty' (VCAA, 2015).

In Years Eleven and Twelve, Critical and Creative Thinking is not taught explicitly but is ‘embedded’ in teaching and learning, and the focus on logical thinking appears to diminish. In the Victorian Certificate of Education (VCE) Physics curriculum document (the ‘Study Design’) it says:

> Critical and creative thinking are embedded in key science skills and applied across the VCE sciences during learning experiences where students develop questions and hypotheses, design and undertake investigations, make reasoned predictions, generate and evaluate knowledge, clarify concepts and ideas, seek possibilities, consider alternatives and consequences, make evidence-based decisions, devise real or imagined solutions, and solve problems. (VCAA, 2022, p. 16)

This raises the question: Is the reduced emphasis on logical thinking in upper-level physics teaching appropriate?’

1.5 The nature of deductive thinking

Before the investigation into logical deduction and physics could proceed, I needed to be sure that I knew what logical deduction *was*. The descriptions of logical thinking given in the literature did not appear to capture the way people think. Instead, they were abstractions of real thinking. The first part of the research, therefore, was a philosophical analysis of this thinking. Nes and Chan (2020) agree that inferring is worthy of greater focus because ‘[it] seems to be central to the life of thought. It allows old thoughts to give birth to new ones…it extends the scope of knowledge, broadening it beyond what is registered by the senses’ (p. 1).

The process of reaching conclusions from premises is also referred to as ‘inference’ or ‘inferring’. Since ‘inference’ can denote both the process and the conclusion, I have used the term ‘infer’ to refer to the process of ‘coming to’ a conclusion from premises. Inferring is also the general term that includes at least two types: deductive and inductive.

Consequently, this research had two approaches, each with its own methodology, methods and results. The first was a philosophical analysis of thinking processes, aimed at giving clarification to deductive inferring. The second was an empirical investigation of physics thinking – the thinking processes used in physics problem solving were studied using a think-aloud method.

2. Literature Review

This research is conducted in the context of research in several domains, including physics education research and research into the ‘thinking classroom’. The need to find better definitions of thinking and inferring also leads to an analysis of the development of these ideas in Western thought from the seventeenth century onwards.

2.1 The challenge of physics education

There is considerable evidence that physics education can be challenging for teachers and students, though the source of the challenge is contentious. Is it perceived to be difficult because it is inherently difficult or is it perceived to be difficult because the of the way that it is taught?

This difficulty has been studied in detail and several facets of it have emerged. In a study by DeWitt et al. (2019), 15 to 16-year-old students were surveyed about their subject choices as they moved into the United Kingdom’s ‘A-levels’. These students had all chosen some science subjects and were divided into two groups – those who had chosen physics and those who had not. 73.3 % of those who had not chosen physics said it was the most difficult of the sciences. Of those who did choose physics, 22.3 % still found it the most difficult science. There was widespread agreement in both groups that physics, culturally, is perceived to be a difficult subject. Interestingly, both groups perceived that physics was an abstract subject, but for the students who chose it, this was part of its appeal.

Angell et al. (2004) surveyed Norwegian upper secondary students and, according to Ornek et al. (2008), they discovered that:

> students find physics difficult because they have to contend with different representations such as experiments, formulas and calculations, graphs, and conceptual explanations at the same time. Moreover, they have to make transformations among them. For example, students need to be able to transfer from graphical representations to mathematical representations (p. 30).

If they are unable to transfer between these representations, confusion will inevitably arise. Lin et al. (2013) also found that students had difficulties translating between mathematical and graphical representations of phenomena.

When Ornek et al. (2008) asked first-year physics students 'what makes physics difficult?', 77% of the students responded along the lines of 'physics is cumulative' (among other reasons). The authors interpreted this statement as meaning 'if you miss one concept, it is hard to grasp the next one' (p. 33). Presumably there are subjects that are less cumulative, where knowledge can be clearly divided into distinct categories. These would allow students to achieve reasonably well even when they miss a concept discussed early in the course.

Roslan et al. (2023) believe that it is the nature of physics that makes it difficult: 'Physics is said to be difficult due to the nature of its knowledge which is very abstract. This is correlated with the low enrolment and lack of interest in Physics courses especially in tertiary level education' (p. 1).[1]

Also, considerable research has investigated the role that misconceptions play in making physics seem difficult or perhaps anti-intuitive. Dykstra et al. (1992) found that often students believe that motion implies force, a conception that is in direct opposition to Newton's first law of motion. Neidorf et al. (2020), in their analysis of data from Trends in International Mathematics and Science Study (TIMSS), found that misconceptions formed in primary school can remain with students and cause problems in understanding in high school. For instance, they found that some high school students retain the misconception that gravity acts only on falling objects and that gravity alone cannot cause an object initially at rest to start moving without another force or push.

Singh and Marshman (2015) found that some of their students' difficulties could be attributed to difficulties in reasoning. An example of such a difficulty was where students used a 'gut' feeling to answer questions instead of explicitly checking the applicability of a physics principle to the situations presented.

Many of the difficulties described above point to a strain on the cognitive abilities of students, also called 'cognitive load' (see Sweller, 2011). Ideas building on other ideas, physics being abstract and physics being mathematical point to the many mental operations involved in the subject. The need for better and more efficient thinking skills is apparent. Also, if students could easily differentiate the purely physics thinking from other types of thinking such as mathematical and logical thinking, they may find the subject more manageable.

[1] *Low enrolment is not necessarily the case in all countries.*

2.2 Improving physics education

The physics teaching community strives to find teaching and learning strategies that enable greater access to the subject and many of the trends in physics education match those in education generally. There has been a shift away from a teacher-centred approach towards a teaching program founded on constructivist principles. The traditional approach to physics teaching was a ‘mimetic pedagogy’ that ‘focussed only on teacher delivered facts in a fixed sequence’ (Chandra and Watters, 2011, p. 632). Yeo and Zadnik (2001) state that ‘it is generally agreed that traditional instruction, which does not take into account existing beliefs of students, is largely ineffective in changing their naïve scientific ideas’ (p. 496). That is, students retain their misconceptions about physics. Hence, there appeared to be a need for student-centred methods that encourage students to reflect on and evaluate their existing knowledge, and construct beliefs.

Many educators advocate a teaching program founded on constructivist principles where students construct their own understandings of physics principles. Calalb (2023) characterises constructivism in the following way: ‘a series of modern methods in which the student “reconstructs” existing knowledge and builds his/her own (scientific or less scientific) vision of the world (p. 141).

McKittrick et al. (1999) show, qualitatively, the effectiveness of a constructivist strategy called Conceptual Understanding Procedure for the learning of physics. They also highlight the importance to student success of an awareness of how they learn – in other words, metacognition. Roslan et al. (2023) advocated the use of Inquiry Based Learning (IBL), a constructivist approach where students behave like real scientists – planning for investigations, presenting results, discussing findings and making conclusions.

It appears, however, that in some cases there was too great a shift towards constructivism. Hattie (2008) found that teacher-oriented and teacher-centred teaching (direct instruction) support learning processes for the development of complex theoretical concepts better than group teaching with discovery learning, such as IBL. That this is the case is particularly plausible for physics concepts – these have often been developed through difficult theoretical and experimental work by exceptional physicists. The independent development of physics concepts, such as Newton's concept of force or Maxwell's equations of electrodynamics, might be too demanding for the students. McGregor (2007) is also critical of some interpretations of constructivism, saying that they concentrate on teacher activities rather than considering the mental processes of the students.

Forbes et al. (2020) observes that ‘meta-analyses and large-scale comparative studies on science education interventions suggest student-directed classroom inquiry may not be as effective as instruction involving significant guidance through science teachers’ (p. 786). The Programme for International Assessment of Students, 2015 (World Bank Group, 2016) considered student achievement in science settings where inquiry-based learning was used, and in those that used more traditional methods. Forbes et al. (2020) analysed this data and found that while high levels of use of inquiry-based learning are relatively uncommon, they are associated with lower student science achievement. Conversely, higher levels of student science achievement are associated with teacher-directed forms of inquiry.

An example of students needing more guidance from their teachers was given by Low and Wilson (2017). They investigated student misconceptions regarding Newton’s Laws of Motion and found that students believed that the normal force and the force of gravity are an action-reaction pair. The researchers believe that this misconception arises when students ‘take two correct statements from their teachers, and infer for themselves a third, incorrect implication’ (p. 23). This suggests that better inferring would lead to more success in reaching correct conclusions. Therefore, greater guidance in inferring by teachers, and a greater understanding of logical implication, would be of assistance.

The conclusion to be drawn is that, despite the noble aims of student-directed inquiry, it does not necessarily lead, by itself, to a good understanding of physics and this is due to the complex nature of the subject. For better outcomes, there needs to be a significant component of teacher directed learning. Nevertheless, the emphasis on the exploration of students’ beliefs and thinking often promoted by IBL should be retained. Assessing student thinking as logical or otherwise, and instruction in this type of thinking, would certainly be an example of this.

It is no surprise that many have focussed on thinking as a means to improve performance in physics. Thinking is central to all facets of physics education, including performance in tests and examinations, and there is evidence that improvement in critical thinking skills is correlated with better performance in tests and examinations. For instance, Ramlo (2019) found that there was a ‘significant correlation’ between the use of critical thinking and performance on Force and Motion Conceptual Evaluation tests (p. 1).

There are many definitions of critical thinking, invoking a variety of thinking skills. Some mention ‘logical thinking’, some ‘reasoning’ and others ‘inference’. For instance, Heath and

Weege (2017) initially define it as ‘meaningful, unbiased decisions or judgments based on the use of interpretation, analysis, evaluation, inferences, and explanations of information as it relates to the evidence applied to a specific discipline’ (p. 206). Mitrevski (2019) believes that ‘critical thinking is one of a family of closely related forms of higher-order thinking, as problem solving, creative thinking, and decision making’ and that it is associated with processes such as ‘reasoning, predicting and analysing’ (p. 1). However, Ramlo (2019) uses the following conception: ‘purposeful, self-regulatory reflective judgment during processes such as analysis, evaluation, and inference’ (p. 196).

Holmes, Wieman, and Bonn (2015), and Ma et al. (2023) found an association between the explicit teaching of critical thinking skills to physics students and their success in the subject. As well, Viennot and Décamp (2020) claim that their research on critical thinking in physics education makes it possible to anticipate or identify reasoning that is not consistent with the physics established by experts, and hence teach the correct reasoning. Lin et al. (2013) found that students’ lack of understanding of a physics law (Guass’s law) was partly because textbooks did not ‘sufficiently emphasise … the chain of reasoning required to determine if Gauss’s law is useful for finding the electric field’ (p. 2). In response to this, the researchers devised a tutorial program that leads students through these chains of reasoning – clearly the teaching of logic.

It appears that the teaching of critical thinking/reasoning to physics students helps them counter some of the difficulties of the subject. However, as stated above, the term ‘critical thinking’ is an umbrella term, encompassing a variety of thinking skills. A more targeted approach to the teaching of these skills is worth exploring. With a narrow focus on logical thinking, students could identify when they are using, or attempting to use, this type of thinking and more readily improve it. As well, such efforts would be improved by having clearer definitions of this logical thinking.

A focus on logical thinking may also help resolve some of the difficulties found by Angell et al. (2004). If success in physics does require a wide range of skills, having students focus on these skills individually, rather than simultaneously, could be beneficial. So, if logical thinking is involved, the explicit teaching of this skill would likewise be of assistance.

Some researchers have found that teaching students how to use metacognition assists in the learning of physics. Zhang et al. (2023) define the process as ‘students’ judgment of their knowledge and awareness of their learning process’ (p. 1). Peña-Ayala (2015) states that metacognition is used to ‘monitor and regulate cognition engaged in a given mental activity (e.g., listening, reading, memorizing)' (p. v). Ali et al. (2014) investigated the use of this process in a think-aloud study involving students who were completing physics problem solving tasks and found that greater metacognition did lead to improved performance. Sukarno and Widdah (2020) also found that student use of metacognition had a significant impact on their achievement levels. These studies imply that greater use of metacognition, such as thinking about one's logical thinking, will lead to enhanced understanding of physics and gives more grounds for believing that teaching students how to think logically could lead to improved outcomes in physics education.

2.3 The logical structure of physics

Another reason for believing that deductive inferring may be of assistance in studying physics is the logical structure of physics theories. Sneed (2012) reflects that a widely accepted claim about scientific theories is: 'The logical relations among the statements of a scientific theory may be exhibited by an axiomatic system' (p. 5). The axiomatic system would contain the laws of physics and from these someone could deduce the behaviour of particular objects. This is like the way a mathematician can make deductions, say, from the axioms of Euclidean geometry. Viennot and Décamp (2020) agree with this analysis, stating: 'physics is a very structured science where a few laws make it possible to account for many situations' (p. 5). A consequence of this logical structure is that the existence of one state of affairs can imply the existence of another. Hence, knowing the first can allow you to infer the second.

Similarly, Dykstra et al. (1992) clearly see that deductive inferring plays a role in physics thinking. In discussing how a student might realise that a table exerts an invisible upwards force on an object, they say that 'The force is inferred as a result of the logical necessity that similar phenomena should have similar explanations and/or demonstrations and arguments that the table on which the book rests probably bends slightly' (p. 640).

Nevertheless, it is worthwhile assessing the role that deductive inferring plays in *actual* physics thinking before widely advocating its adoption by students – this will be the focus of the empirical component of the research.

2.4 Improving thinking generally

It is important to note that the idea that a focus on thinking is not exclusive to physics education, and the last thirty years have seen many efforts to improve student thinking. Research in this area provides a foundation for further work in devising ways to improve thinking.

The members of Harvard's Project Zero believe that such a focus is necessary because learning only occurs with thinking. Perkins (1995) says: 'learning is a consequence of thinking. Retention, understanding, and the active use of knowledge can be brought about only by learning experiences in which learners think about and think with what they are learning' (p. 8).

Nickerson (1988) agrees that a principal focus of schools should be thinking: 'The teaching of thinking … should be a fundamental, if not the fundamental, goal of education' (p. 9). He believes this because 'the development of whatever potential one has to think well and independently is a desirable objective for everyone' (p. 9).

McGregor (2007) believes that students can already think, but by 'teaching about thinking, reflecting on thinking processes and modelling good thinking, educators can help learners develop better quality thinking' (p. 40).

These authors also promote strategies to improve the quality of student thinking and some of these strategies have elements of instruction in logic. Tishman et al. (1993) advocated the cultivation of thinking *dispositions* in students. Cultivating these makes students more aware of their thinking patterns and give them a better understanding of what good thinking is. The thinking disposition that is most relevant to this study, given its focus on deduction, is the disposition to 'reason clearly and carefully'. Having this disposition means that students have a desire to 'seek clarity, gain understanding, be precise, be thorough and remain alert to possible error' (p. 42). I believe that to 'reason clearly and carefully' aligns with the aims of this research.

Project Zero propose that student thinking should be 'made visible' so that it can be more properly assessed and then improved upon. To be 'visible' is to be brought to a form that can be perceived by others, so includes all the senses, not just vision. 'When we make thinking visible, we get not only a window into what students understand but also how they are understanding it' (Ritchhart e al., 2011, p. 26).

Ritchhart et al. (2011) identify eight ‘thinking moves’ that they believe are key to learning. The one that is relevant to this study, ‘reasoning with evidence’, is where students give explanation for their points of view. The authors elaborate on this process: ‘In building these explanations, we draw on and reason with evidence to support our positions and try to arrive at fair and accurate positions that can be supported’ (p. 12). They have also devised several *Thinking Routines* to enable students to materialise their thinking more readily. For instance, a routine that utilises the ‘reasoning with evidence’ move is ‘What makes you say that?’, giving students practice in justifying their point of view. I think this activity could be enhanced if students were given an understanding of the difference between deductive and inductive justifications, particularly the difference in the strength of these.

Beyer (1998) has similar suggestions to Project Zero: provide thoughtful learning environments, make thinking visible and scaffold student thinking. Bruner (1996) articulates some of the thinking skills which students need to practise in order to improve: ‘plausible guessing, the use of the heuristic hunch, the best employment of necessarily insufficient evidence – these are the activities in which the child needs practice and guidance’ (p. 126). Zohar (2004) proposes the explicit teaching of higher order thinking skill to improve performance in science subjects.

I believe that the improvement of thinking would be well served by a better delineation of thinking – one that describes it as a mental process. The above descriptions lack an acknowledgement of the processes that occurs in the mind of the thinker – the mechanics of the mind. For instance, such a description of inferring might be ‘the production of a new belief from some other beliefs.’ This at least suggests a process occurring in a mind. Consequently, this research aims to give a better delineation.

Another element of the increasing focus on thinking has been the recommendation that logic be taught to all students. Gensler (2012) gives three main reasons for learning the skills of logic. The first is to help students understand reasoning and become better at it. He mentions the importance of ‘reasoning and general analytical skills in law, politics, journalism, education, medicine, business, science, mathematics, computer science, and most other areas’ (p. 1). The second is to deepen student understanding of philosophy and the third is because it can be fun. The implication of this is that logic education should not be restricted to students of philosophy – any of the areas mentioned above, including science, would be poorer for a lack of it. Quintana and Schunn (2019) provided evidence of this. Their study shows that the completion of an introductory undergraduate logic course is associated with an increase in students’ general academic performance. Marzano

(2010) also places great importance on the skill of inference (inferring): ‘we’ve become aware that some cognitive processes are foundational to higher-order thinking. Inference is one of those foundational processes’ (p. 80). He then suggests how to assess these inferences – by identifying premises and considering validity.

The common threads of reasoning, critical thinking and higher order thinking skills through these approaches give more justification for applying deductive inferring to the teaching of physics. However, it is first important to gain conceptual clarity around the terms ‘thinking’ and ‘inferring’. This will allow the development of methods for improvement of these to proceed more efficiently.

The next sections consider the development of ideas about these terms.

2.5 The nature of thinking

Thinking is a process that is considered to occur in a mind. Consequently, the nature of mind and the nature of thinking are closely related. In Western philosophy, there have been two principal theories of mind that I will refer to as the *non-material* and *material* views. The non-material or dualist view, as propounded by Descartes (2013), is that thinking is not a property or phenomenon of the physical universe, and that it, therefore, must occur in another, non-material realm. Our thoughts, therefore, are configurations of a mental substance, in the same way that physical objects can be construed as configurations of a general physical substance (matter). Descriptions of thinking are, therefore, necessarily phenomenal – they describe mental objects such as beliefs and memories, and mental processes such as inferring and wondering.

Conversely, the materialist views says that the only substance in the universe is physical substance, and any phenomenon, including thinking, must be a purely physical phenomenon. This theory strongly disputes the notion that humans have a separate mind and body. The mind is a phenomenon of the brain, which is clearly part of the body.

Modern science gives us grounds for rejecting the non-materialist view, since it says that there is only one substance, and, therefore, for believing that thinking is a purely physical process. The scientific understanding is that physical processes of the brain (for example neurons firing) constitute what we call thinking. Armstrong (1981) affirms this view, believing that we can give ‘a complete account of man in purely physico-chemical terms’ (p. 1).

Peña-Ayala and Cárdenas (2015) also agree with this view, stating that 'cognitive abilities are neural processes, which are represented and performed in the brain' (p. 53).

Does the rejection of Descartes' dualism also necessitate the rejection of the phenomenalist description of thinking as a *scientific* description? The theory of behaviourism does suggest this. It holds that thought is an unobservable phenomenon and, consequently, not worthy of scientific investigation. Watson (1913) believed that, for psychology to be a science, it needed to remove all reference to mental states: 'The time seems to have come when psychology must discard all reference to consciousness; when it need no longer delude itself into thinking it is making mental states the object of observation' (p. 163).
According to behaviourists, the only thinking phenomenon that is worthy of such investigation is behaviour, as this can be observed by several people at once. Behaviourists would also now allow scans of brain activity as observation of thinking, as this is observing a physical phenomenon.

According to the first versions of behaviourism, the phenomenalist language that had been used to describe thinking throughout history is meaningless. This is reinforced by Wittgenstein (1992) who discredits the idea of describing private mental states in the same way that we describe physical states. However, after an initial equation of mind with behaviour, it was soon realised that psychologists needed to attribute more than just behaviour to an individual. Ryle, therefore, introduced the notion of a *disposition.* A person is said to have a certain disposition (for example, being quick to anger) when it is observed that, given a certain situation, certain behaviours are likely to ensue. He was very keen to point out, however, that the disposition was not an inner mental state.

Armstrong (1981) produced a counterargument to the purely behaviourist view of dispositions. He used the example of the brittleness of glass. This is both a disposition of the glass (given certain circumstances, it will break) and a property that can be attributed to an 'inner state' of the glass (its atomic or molecular structure).

Armstrong suggested that it would be equally appropriate to posit that there is an unseen physical state that corresponds to a psychological disposition. Importantly, this disposition can be part of a causal explanation for behaviour. For example, an angry outburst could be explained by referring to a situation a person was in and the disposition of being quick to anger. This disposition could be a physical state of the central nervous system. Furthermore, could not all behaviour have corresponding states of the central nervous system as a partial or whole cause of this behaviour?

A mental state, therefore, could correspond to (or be) a physical state of the brain. Equally, thinking could correspond to (or be) a physical process of the brain.

Armstrong (1981) also gave a case for the theory that humans can be personally aware of some of their mental states. Just as our brains can be aware of the 'external' environment (for example seeing a tree), they can also be aware of these perceptions. The perception of a tree or other physical phenomenon involves impulses being sent from our sense organs to a part of our brain (X). A consciousness of this perception would involve another impulse or impulses being sent from part X to another part of our brain part Y. So, we could say that while part X perceives the tree, part Y perceives that part X perceives the tree. But perceptions are not the only object of consciousness – we can be aware of many other mental states such as memories, beliefs and emotions. Armstrong suggests that consciousness is a self-scanning mechanism of the central nervous system: 'So I have argued that consciousness of our own mental state may be assimilated to perception of our own mental state' (p. 14).

This theory opens up a great possibility for cognitive science: if we are aware of our own thought processes and mental states, we may be able to describe these – in the phenomenalist way most people do – giving us insight into the processes of our brain. In this research, I will be using the self-reporting of mental states as a means of gaining insight into thinking processes.

In summary, thinking can be defined as nerve impulses in the brain. These nerve impulses can be of sufficient complexity and interconnectedness that they can give rise to conscious experience.

It should be noted that some philosophers (for example, Dennett, 1989) have suggested that it is possible to discuss thinking without committing to a particular ontology regarding the nature of 'mind'. For instance, the existence of a belief would not be thought to entail the existence of a brain state nor the existence of a particular state of some mental substance. However, the material theory presented seems the best candidate for giving a theory of thinking a scientific basis.

2.6 The nature of inferring

As one of my aims is to determine whether deductive inferring (logical deduction) is part of physics thinking, this type of thinking will be the main focus of the philosophical investigation. Although many types of thinking occur in the physics classroom, I wondered whether deductive inferring plays a significant role in this learning domain.

Following from the previous section, I will assume that, as a type of thinking, inferring is collection of nerve impulses occurring in the brain. It is also a process of which we are sometimes conscious. Some have wondered whether this process is well defined at all. For example, Baserer (2020) says: ‘there is no certainty in the literature about what logical thinking is. For this reason, there are many definitions related to logical thinking’ (p. 177).

I am assuming that such thinking is a type of inferring. To infer is to ‘form an opinion or guess that something is true because of the information that you have’ (Cambridge University Press, n.d.). An example of inferring is coming to the belief that a certain person is walking by from the sound of their footsteps. It is clearly a mental process, where one comes to beliefs that go beyond what can be immediately perceived or read.

2.7 Deductive Inferring

I take deductive inferring to mean moving from premises to conclusion according to one of the known logical laws or syllogisms. As stated in the introduction, the distinctive nature of this inferring is that the truth of the premises is thought to guarantee the truth of the conclusion. Franks et al. (2013) agrees: ‘Logical reasoning involves determining what would follow from stated premises if they were true’ (p. 146). By ‘what would follow’, I assume that Franks et al. mean: what would *necessarily* follow. Similarly, Ormerod (2010) says (under the heading ‘Deductive Inference’): ‘Deductive logic refers to arguments that are certain to be true by definition. It includes philosophical logic and mathematics. No empirical evidence is required for a proof’ (p. 1209). ‘True by definition’ is equivalent to “necessarily follows”.

For example, consider again the deduction:

> *All humans are mortal, and since Socrates was a human, he was also mortal.*

A deduction is formally referred to as an *argument*. The following is the above argument written in syllogistic form:

> *P1: All A’s are B*
> *P2: x is an A*
> *C: Therefore, x is a B*

If the premises are true, a rational person would be constrained to accept the conclusion. It does not matter what the A, B or x are, it is the structure of the argument that is important. Such an argument, where the conclusion is a logical consequence of its premises, is classified as a *valid* argument. For a conclusion to be a logical consequence requires the following condition to be satisfied: when the premises are true it is impossible for the conclusion to be false. Note that this condition does not require that the premises *are* true, merely what must be the case *if* they are. If the conclusion is not a logical consequence of its premises and yet the argument *seems* convincing, it may be because it commits a logical fallacy, such as affirming the consequent.[2]
Beall (2017) defines validity in the following way: 'Traditionally, an argument is said to be valid – strictly speaking, logically valid – if its conclusion is a logical consequence of its premises. We will follow suit' (p. 8). To decide whether an argument is valid or not, 'truth tables' are used, an example of which is given in the Appendix.

Nevertheless, a valid argument can be rejected if one of the premises is false. A *sound* argument, on the other hand, is 'valid and all its premises are true.' (Beall, 2017, p. 8). Validity is necessary, but not sufficient, for an argument to be successful whereas soundness is a necessary and sufficient condition. It is thought that a sound argument cannot be rejected by a rational person. In the case of the argument given above regarding Socrates, it is definitely valid, as it clearly has the form given in the syllogism. We may be able to say that it is not a sound argument, on the basis of the rejection of the first premise. Can we really say that every human that has ever existed or will exist is mortal?

The following is an example of a sound argument:

P1: The Eifel Tower is in Paris
<u>*P2: Paris is in France*</u>
C: The Eifel Tower is in France

This is valid, as it follows the following valid syllogistic form:

P1: x is in A
<u>*P2: A is in B*</u>
C: x is in B

[2] *This will be explained in Chapter 5.*

If both premises are true, then the conclusion cannot be false. As well, the premises *are* true – the Eifel Tower is in Paris and Paris is in France. This argument, therefore, is sound. It would be possible for someone who had not previously known that the Eifel Tower is in France to come to this conclusion after being told that the Eifel Tower is in Paris and that Paris is in France.

If an argument is sound, then the conclusion is true. It follows that if people consciously use logical deduction (valid reasoning) to reach conclusions from *true* premises, then the conclusions will be more than 'mere' beliefs. One could have complete confidence in them. It is this guarantee of certainty that renders logical deduction such a potentially powerful thinking tool. Philosophers have identified a class of syllogisms that, together, are thought to describe logical reasoning and which are a means to deduce correctly.

The consequences of this for education, if true, are profound. It would mean that, were students to use logical deduction, using true premises, then they could have complete confidence in their answers. The implementation of logic would enable them to answer test and examination questions correctly with ease (assuming that their content knowledge was complete).

Unfortunately, there are reasons for believing that such a guarantee does not exist. One reason is the scepticism that Wittgenstein (1992) promotes regarding the certainty of these conclusions.[3] This doubt has led to the quest to find a better delineation of logical deduction in the present research, and is a precursor to exploring the role of logical deduction in physics thinking.

2.8 Inductive inferring

As stated in the Introduction, deductive inferring is contrasted with *inductive* inferring. In the latter, the conclusion is only *probably* true when the premises are true – there is a possibility of the conclusion being false. Baserer (2020) agrees that deductive inferring is usually differentiated from inductive inferring by referring to the certainty of the conclusions. The reason for this lack of certainty in inductive inferring is the use of generalisation. Ormerod (2010) says that inductive inferring 'is usually defined as inference from the particular to the general' (p. 1210) and was shown by David Hume to 'lack justification' (p. 1211).

[3] *This scepticism will be discussed in detail in Chapter 5.*

Consider the following famous example attributed to Hume:

P1: Every swan I have ever seen is white

P2: Peter has a swan

C: Peter's swan is white

In this argument, it is not the case that, if the premises are true, the conclusion must be true. The difference between this case and the Socrates case given above is in the first premise. If the first premise here had been 'All swans are white', it would include swans not seen by me as well those that have been – a potentially infinite number of swans. 'Every swan I have ever seen' is a number that may be large but cannot be infinite. The fact that every swan I have ever seen is white may make me confident that Peter's swan is white, but I cannot know that it is true. Inductive inferring does not, therefore, have a truth guarantee. This is not to say that we do not employ inductive inferring – we use it every day.

Hume (2023) realised that a conclusion reached via inductive inferring lacked the certainty of those reached via deductive inferring. He noted that there is no necessary connection between inductive premises and conclusions. Rather, it is a habit of our minds to come to inductive conclusions, not a matter of logical necessity. Any conclusions brought about by inductive inferring are not *necessarily* true and, therefore, dubitable.

The problems for deductive inferring that I suggested may exist, in terms of a guarantee of truth, also apply to inductive inferring. Therefore, there are two reasons to doubt conclusions brought about by inductive inferring.

The distinctions mentioned above between valid and invalid arguments and between deductive and inductive inferring were deemed important enough by the VCAA to include it in the Victorian Curriculum for Grade 5 and 6 students: 'Examine the difference between valid and sound arguments and between inductive and deductive reasoning, and their degrees of certainty' (VCAA, 2015).

2.9 Observing thinking

As suggested above, one means of exploring thinking is introspection. This method has gained ground in the last thirty years as an empirical method for exploring thinking, though it has not been without controversy.

The idea that such research is *empirical* was criticised by Skinner (1965) and Ryle (2009). They wanted psychology to concentrate only on observable behaviour, not unseen mental events. However, Ericsson and Simon (1980) show that it is very difficult for psychology to avoid some reliance on verbal reports of this invisible realm: 'Verbal responses … provide the basic behavioural data in standard experimental paradigms' (p. 216).

In the last thirty years, the systematic study of conscious thought has regained credibility. For instance, Wolcott and Lobczowski (2021) say: 'These systematic methods provide opportunities for researchers to codify thinking and performance to then address questions about decision-making and other thought processes' (p. 182). Green et al. (2017) argue for the use of this methodology as a powerful tool, among many, for capturing and modelling the dynamic aspects of self-regulation of learning.

A research method in this vein is the think-aloud method or protocol (see Methodologies). In this, participants verbalise their thinking while completing a challenging task. It has considerable potential for utilisation in a study on physics thinking and it has been used in this study.

2.10 Research Questions

The literature surveyed shows that, while there have been many efforts to counter the difficulties that students face in physics, and to improve the thinking of students in all disciplines, the teaching of logic as a thinking skill is worthy of more attention, particularly in relation to physics education. Furthermore, there is a lack of clarity around the concepts of 'thinking' and 'deductive inferring' in educational contexts. This research aims to address these shortcomings.

Since I wished to see the role of logical deduction (deductive inferring) in physics thinking, it was important to first have a clearer understanding of it as a *thinking* process. The first research question is, therefore:

> *What is logical deduction? How is it different from other thinking processes?*

Consequently, the first part of this research is devoted to a philosophical investigation of deductive and inductive inferring.

To explore the potential application of logical deduction to physics education, the second part is an empirical investigation into a mode of thinking in physics education – that of answering questions in examination conditions. This answers the questions:

> *What type thinking occurs when answering physics questions in an examination context? What is the role of logical deduction in this thinking?*

The context of the physics examination was chosen because the thinking in this context occurs privately and without immediate feedback on the correctness of the thinking. Other types of thinking in the physics classroom may be directly influenced by other students, the teacher and the ability to get immediate feedback on the correctness of thinking (for instance, by checking the answers in the textbook). The importance of a context involving 'private' thinking becomes more apparent once the nature of inferring is explored in the Philosophical Investigation.

The findings of these two parts will be used to answer the third question:

> *Should logical deduction be taught more explicitly in physics classes?*

This will be considered in the Discussion chapter.

3. Methodologies

A methodology needs to provide an epistemological and ontological framework in which the subject matter under investigation sits comfortably. There are two distinct methodologies in this research – one for each of my research questions.

3.1 Philosophical investigation methodology

The methodology employed in the conceptual part of this research is philosophical research in the Analytic tradition, one that is appropriate when the object of the research is a network of concepts. It makes few, if any, epistemological and ontological assumptions – in fact, in philosophy it is often these domains that themselves are being questioned. This is particularly the case with the investigation of inferring. Inferring is a mental activity that involves the formation of beliefs, and belief formation is an essential concept in epistemology. In fact, the epistemological framework for the second part of the investigation (the empirical work) is prepared in the first part. Golding (2015) defines the activities of philosophical research: ‘we construct concepts, theories and argument, employing logic and reasoning to resolve conceptual and normative problems’ (p. 206).

To describe thinking accurately, greater clarity is required around many concepts related to thinking and the relationship between thinking and the ‘external’ world. Therefore, concepts such as ‘infer’, ‘state of affairs’, ‘belief’, ‘truth’, and ‘certainty’ need to be explored. Another part of the research is to determine the role that deductive inferring has in thinking about physics. Therefore, it is also important to establish the meaning of the terms ‘infer’ and ‘deductive’.

This philosophical analysis is crucial to my overall aim of describing the thinking in physics. Without an initial clear understanding of the meaning of thinking terms, it would be meaningless to classify certain thinking episodes as a particular type of thinking. Philosophy is also crucial in guiding the development of new ways of describing thinking.

3.2 Empirical investigation methodology

The research undertaken in the second part of this study was a type of Observational Research and more specifically Systematic Self-Observation, as described by Loveikaite et al. (2023). This is appropriate given that the thinking used while completing physics problems was self-reported using a think-aloud method (see Ericsson and Simon, 1993). Such research is embedded in the empirical paradigm, for if it is accepted that thinking is a physical phenomenon (and I do think this should be accepted), then descriptions of thinking are, potentially, descriptions of an objective physical reality and this research can be considered empirical research. Max Weber (1978) agrees, identifying mental 'behaviours' as one of the subjects of Systematic Self-observation. By considering several similar thinking episodes, patterns of thinking processes can be inducted. The theories of thinking developed are grounded in these empirical results.

The methodology is potentially problematic. It is possible that, instead of simply reporting the cognitive processes occurring, thinking aloud is *enhancing* these processes. If this is the case, it would be very helpful for students to adopt the strategy, but it would provide a challenge to the categorisation of this methodology as an *empirical* methodology. Nevertheless, there have been other studies that have found no such enhancement or diminishment as a result of thinking aloud and, as discussed in the Literature Review, it is now considered an empirical methodology.[4]

It is also important to note that this research does not fit a traditional empirical model of repeated observations of phenomena and reproducibility. The data cannot be observed by more than one person and each instance of thinking is not repeatable – the same physics question cannot be tackled as a 'new' question twice (in a short time frame). It may, therefore, be apparent that it would be difficult to generalise any findings. However, it may be seen as a 'proof of concept' for future studies. It can also be argued that results of this type of research can be generalised to other thinkers. Different humans think in similar ways because our brains are similar – a simple biological fact. Our ability to understand someone explaining their thinking to us also corresponds with this idea.

The phenomenalist description of thinking has a long history. It was the type used by Descartes and Hume in their analyses of thinking. The physicalist or reductionist description is much more recent and came about with the rise of modern science. In literature that is addressing the need to improve thinking, such as that of Ritchhart et al. (2011), the language is definitely phenomenalist. I am, therefore, addressing this type of description and the need to improve such descriptions.

Theories of consciousness, as detailed in the introduction, give support to this methodology. Armstrong (1981) views consciousness as 'perception or awareness of the state of our own mind' (p. 14). If this is true, then it would be possible for one part of the mind to observe the workings of another part. For instance, it would be possible to, simultaneously, think about a

[4] *These studies will be further discussed in Chapter 4.*

physics problem and to observe this thinking. This implies that introspection is not psychologically and epistemically different from regular belief formation.

Of course, it is not logically possible that a person could fully describe the current workings of their mind, as the act of describing is itself a mental activity. To fully describe the activity would involve an infinite regress of ‘describing’. Any research in this area will need to limit itself to a particular mode of thinking, which I have done.

4. Methods

To be clear about the concepts being employed in this research, the philosophical method was used to explore the concepts of thinking, inferring and, more particularly, deductive inferring. Then an empirical method was employed to 'observe' some thinking episodes – a method that followed the principles of the 'think-aloud protocol'.

4.1 Philosophical investigation method

The method used for the philosophical investigation is philosophical analysis in the tradition of Analytic philosophy. Connelly (1973) gives support for such philosophical analysis in this field, as he believes that 'philosophical … perspectives, are of primary importance to science education' (p. 278).

The method involves applying logical analysis to a field of study and attempts to give a logically consistent account of a topic. To achieve this, the logical consequences of viewpoints are explored. To be sure of these consequences, clarity of concepts is initially crucial.

Beaney (2017) refers to the idea of *rigour* in philosophy and explains that philosophers should:

> try to get as clear as they can about the philosophical issues that they address, to express their ideas as precisely as possible (using both ordinary language and technical vocabulary, as appropriate), and to present their arguments with the maximum degree of rigour. (p. 1)

But to make a contribution to philosophy, you also need to be conceptually creative. That is, you need to search for concepts that allow one to increase the clarity and depth of thought and 'lead to fruitful applications and the development of more systematic theories' (p. 2).

The focus for this section was the thinking process of deductive inferring. It was considered in the light of our current understanding of the relationship between psychological states (such as belief) and states of the 'external' world. The concepts of truth and knowledge were explored, and the process of inferring was analysed using Wittgenstein's approach to rule-following (see Wittgenstein, 1992). The epistemological status of the products of inferring could then be considered.

Next, the possibility of different types of inferring (deductive and inductive) was considered and, given the confusion of the terms 'inferring' and 'logical implication', a critical comparison of inferring and deductive logic is undertaken. Such analysis requires considerations of the nature of the physical world, the mental realm and their interactions with each other.

4.2 Empirical investigation method

The thinking of interest in this study is that which occurs while a person answers physics questions on an examination. This thinking has been chosen because there is no immediate feedback on the correctness of the thinking – we can be confident that the outcomes (answers) are the result of mental activity devoted to the questions given (and possibly random guesses), and not partially as the result of input from other people, a teacher or observations during a practical activity. It is expected that a range of thinking types occur in answering the mathematical, visual and conceptual questions that occur in these examinations.

The method used for this investigation is introspecting and verbally describing mental activity. While this was not a popular method for much of the twentieth century, due to the rise of behaviourism, it has made a resurgence in recent times.

The earliest empirical investigation of reasoning was carried out by Cutsforth (1924). Two subjects reported introspections during a variety of reasoning tasks. Although the two subjects differed in the extent to which they reported visual, kinaesthetic, and verbal imagery, 'no functional differences in reasoning between the observers were found' (p. 97).

The resurgence of the introspective method in recent years is largely due to the work of Clayton Lewis, K. Anders Ericsson and Herbert Simon. They devised the *think-aloud protocol* in which a participant verbalises their thinking while carrying out a complex mental task – this is called concurrent verbalisation (as opposed to a verbalisation of prior thinking). Ericsson and Simon (1993) put their faith in this method because they believe that the stimulus-response investigations of the behaviourists give little information about the mechanisms of the mind: 'After a long period of time during which stimulus-response relations were at the focus of attention, research in psychology is now seeking to understand in detail the mechanisms and internal structure of cognitive processes that produce these relations' (p. 1).

There were several challenges for the success of this method. There was the question of validity and reliability – how can we be sure that a verbal report of thinking accurately represents what is 'really going on'? There was also a question of whether the act of verbalising interferes with the thinking activity. Lastly, there was the possibility that some thinking is not able to be reported verbally – for instance sudden insights – meaning that the method would not give a complete description of mental activity.

According to Fox et al. (2010), Ericsson and Simon have responded to these challenges in several studies where they have sought to find methods that allow the participants to verbalise their thoughts in a manner where 'the sequences of thoughts are not influenced and thus the accuracy of performance is unaffected' (p. 318).

Fox et al. (2010) undertook a meta-analysis of studies that assessed the think-aloud protocol. They found that such concurrent verbalization 'does not influence the accuracy of performance and, by implication, does not alter the cognitive processes mediating task performance' (p. 335) and concluded that the 'think-aloud verbalization delivers information about the cognitive processes and thoughts mediating solutions under silent conditions' (p. 335).

Perkins (2009) provides a method for verbalising thinking, and this was used in this research:

> The method begins with instructions organized into six principles. The first three promote a complete record and the second three discourage over-explanation:
>
> 1. Say whatever's on your mind. Don't hold back hunches, guesses, wild ideas, images, intentions.
> 2. Speak as continuously as possible. Say something at least once every five seconds, even if only, "I'm drawing a blank."
> 3. Speak audibly. Watch out for your voice dropping as you become involved.
> 4. Speak as telegraphically as you please. Don't worry about complete sentences and eloquence.
> 5. Don't over explain or justify. Analyse no more than you would normally.
> 6. Don't elaborate past events. Get into the pattern of saying what you're thinking now, not of thinking for a while and then describing your thoughts. (p. 33)

To investigate thinking in physics, I verbalised my thoughts while completing thirteen short answer questions from a Victorian Certificate of Education final year Physics examination (VCAA, 2019). The data analysed consists of a video recording of writing and drawing on the examination paper while verbalising my thoughts. The camera was focussed only on the writing and drawing. This procedure enabled the correlation between the verbalisations and the writing process to be clearly seen. The questions had not been seen before and they were answered alone in examination conditions. As well, the solutions to these questions were not accessed until the question was completed.

Figure 1 shows the how the camera was trained on the paper.

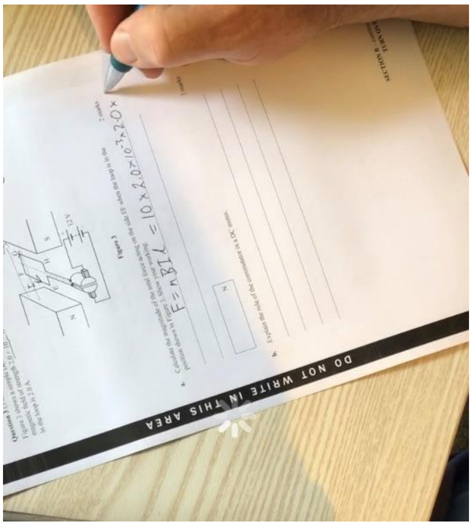


Figure 1 (Image: the author)

The video was then played back so that a verbatim transcript of the verbalisations for each question could be made.

I chose to not involve multiple participants in this study as the aim was to develop methods of describing thinking using an appropriately mental vocabulary. There is some attempt to produce reliable results in that multiple questions were answered and the thinking for these was compared. It was, of course, possible that no patterns would emerge and that the thinking for each problem was unique.

The think aloud method is aligned with Project Zero's suggestion of 'making thinking visible'. The transcripts will be a representation of the thinking processes used in answering the questions.

5. Results and Analysis 1: Philosophical Investigation

5.1 Introduction

This chapter details the results of the philosophical clarification of the nature of deductive inferring (logical deduction). Such a delineation is requisite for the determination of its role in physics thinking. It involves analysis of the terms 'infer' and 'deductive' and, as inferring involves belief, an exploration of the nature of belief. The main question considered is: Can inferring produce conclusions that are known to be true? I argue that, when inferring is carried out privately, such knowledge is unattainable.

Epistemology is the relevant philosophical domain for this investigation as it considers the nature of mental states such as 'belief' and 'knowledge'. But, as belief and knowledge are often about the world beyond our minds, epistemology also considers the relationship between these mental states and the 'external' world. It is important, therefore, to provide a statement of the assumptions I am making in this epistemology.

5.2 Epistemology

In the Literature Review, I concluded that thinking is a purely physical process. However, it was also recognised that consciousness is an element of human thinking and that, by this process, we can be aware of our own thinking. This awareness of our thoughts is restricted to one person and so our mental world is a private world. The contrast between this 'inner world' and the 'outer observable world' is essential to the epistemology I am using in this thesis.

Prior to the analysis of the epistemology of inferring, it is important to detail the assumptions being made here. I am assuming that the 'outer observable world' mentioned in the last paragraph exists independently of our observations of it. It is the theory held by much of the scientific community and some philosophers of science. For instance, Popper's (1963) theory of scientific progress gives much support to it. I do acknowledge that quantum physics has provided challenges to this view, but in this limited research I cannot debate that issue. I am also assuming that our minds construct representations of this outer world, which we refer to as beliefs or models.

Cognition, then, can be viewed as a description of the relationship between our mental states (such as beliefs) and the actual state of the world – that is, an account of how accurately the mental states depict the state of the world. This is known as the correspondence theory of truth. In the following sections, I will define the terms used in the analysis of this relationship and then explore the nature of belief and inferring.

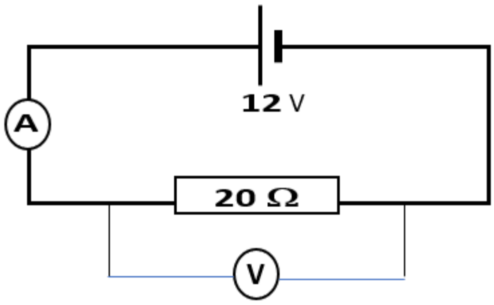
The ‘actual states of the world’ that I referred to are the many arrangements of matter and energy through time in the universe. I will refer to these as ‘states of affairs’. An example of a state of affairs is ‘the Earth orbits the Sun once every (approximately) 365.25 days’. Propositions are sentences that represent these states of affairs.

As detailed above, the mental ‘space’ where we experience perceptions, images and feelings (among others) appears to us as separate from the ‘external’ physical world – there is a distinction between the physical world and the ‘space’ of our consciousness – a ‘space’ that we still experience when our eyes are closed. This is why Descartes had difficulty reconciling the two, and theorised that the mental realm was not physical. I will, however, assume that our consciousness is, fundamentally, a physical process. I will also assume that there is a possibility that our perceptions of the external world and the *actual* external world do not necessarily match. Another way of saying this, adhering to physicalist principles, is that physical processes in our brain can generate false beliefs about the physical world.

What is it to have a belief? Humans have the ability to mentally represent actual and possible states of affairs. Our minds attempt to model the world and these models probably consist of beliefs. Schwitzgebel (2023) defines a belief as the mental acceptance or conviction in the truth or actuality of some idea, while Stephens and Graham (2004) suggest that ‘beliefs possess representational content, for instance, they represent the world or self as being, or possibly being, a certain way’ (p. 237). Beliefs, therefore, can be true or false (or unable to be determined as true or false).

Truth is a controversial concept in philosophy and a full treatment of it is beyond the scope of this thesis. I will be using the term in a way that is consistent with the ontological position given above – that the world exists independently of our minds and exists in states of affairs. I will assume that a belief is *true* when the state of affairs represented by it is the case and *false* when the state of affairs so described does not exist. To determine whether a belief is true, it must be *verified* or *falsified* in some way. For example, a simple verification of the belief that there is a red cup on the bench (when this is true) is going to the bench, looking and, possibly, picking up the cup.

There is a different test for the veracity of beliefs about hypothetical, idealised situations, such as physics questions in an examination. The state of affairs described in the question is not extant and so cannot be verified by observation. In these cases, it may be advantageous to use the term ‘correct’ rather than ‘true’. The criterion of correctness could, instead, be ‘that which is agreed upon by a community of experts’. For instance, consider the question about a circuit diagram shown in Figure 2:



What would the reading on the ammeter be?

Figure 2

As there is no *actual* ammeter, there is no way of checking the answer via a simple verification. Instead, correctness would be defined, ultimately, by the agreement by the community of physicists that a certain value is correct.

The term ‘know’ is also controversial and not one that can be dealt with adequately in this thesis. I will be using the term only for those beliefs that coincide with those of a large portion of the general community (particularly the scientific community) and those that are established via our senses when we are fully awake. To highlight the difference between this conception of knowing and merely believing, consider the following example. Imagine that mail delivery is accompanied by a particular whistle sound. On hearing that sound, one might come to a belief that there is mail in the mailbox. Another way to come to that belief is by examining the mailbox. It can be argued that the propositional content of both beliefs is the same (there is some mail in the mailbox), but also that the belief gained by looking is *knowledge* while that from hearing the whistle mere *belief*. We would be reluctant to say that we *know* that there is mail in the mailbox without seeing it there (or some other means of verification).

Regardless, the question of whether knowledge is possible is somewhat moot in this thesis. Even if it is possible, I will be arguing that, when used in inferring – even deductive inferring, it does not result in new pieces of knowledge.

Another element of epistemology to consider is certainty. It may be thought that knowledge involves certainty, as people often use this notion to assist them in convincing others to share their beliefs. Does a high level of certainty necessarily make a belief more probable? I would say not. It is uncontroversial to assert that people are sometimes very certain about a belief that is false. An example of this is the certainty that people had that the Earth was stationary and at the centre of the Universe. Certainty, therefore, is not perfectly correlated to the actual truth of a belief.

We are often shocked when a particular belief is disproven and, after the fact, it is possible to point to the circumstances that brought about the belief, which in a sense, excuses the error. However, this does not change the status of the belief as false. This is not to say that feelings of certainty are not helpful. A student completing an examination question may benefit greatly from such feelings – it will encourage their continuation of a certain method of solution, for instance. In terms of analysing the truth status of beliefs, however, certainty is irrelevant.

Having laid the epistemological groundwork regarding beliefs, I am now in a position to consider the status of beliefs that are generated by inferring.

5.3 The nature of inferring

As a type of thinking, I am assuming that inferring is a physical process of the brain. To infer is to come to a new belief as a result of some other prior beliefs, which may be derived from observation, prior knowledge or prior inferring. Humans use this process many times each day and it constitutes a large part of thinking. Seeing footprints in sand (believing that there are footprints in a particular location) may cause us to come to a belief that a person (of a certain size) walked by at some earlier time. We say that we *infer* that a person walked by at some earlier time. There are two parts of the new belief – a belief that an actual or hypothetical state of affairs exists and a belief that the new belief was *caused* by the first belief. That is, we are usually able to explain why we have come to the new beliefs. As we can be sceptical about any beliefs, we can question whether this causation existed.

In the case given previously, where the belief that the net force is zero arises from the belief that the object is travelling at a constant velocity (which, say, came about by reading this information), it appears likely that the new belief (the net force is zero) arose from the read statement in combination with the belief, held as prior knowledge, that when any object is travelling at constant velocity the net force acting on it is zero.

In both cases above, there appears to be a difference between the truth status of the original belief and the inferred belief. We would struggle to doubt that we see certain shapes in the sand, but we could admit, if pressed, that there is a possibility that these marks could be produced by something other than a human walking (they could have been made by someone pressing a shoe down with a stick). It is a common human experience to incorrectly infer from physical evidence and such mistakes are often a source of humour.

Given these differences, it may be that there are no instances of inferring that we can trust absolutely and that none of the beliefs arising from inferring can be known to be true at the time of inferring. For them to be known to be true, the inferring would have to be carried out in a formulaic way from pieces of knowledge – deductive inferring appears, at first glance, to have this characteristic. On the other hand, inductive inferring is thought to result in conclusions that are probable rather than definitely true.

5.4 Deductive inferring

As discussed in the Introduction, deductive inferring is thought of as reasoning that follows a particular pattern, called a syllogism. In such inferring, true premises are thought to result in true conclusions – this is sound reasoning.

Imagine a student reporting on their performance on an examination question. They may say: 'I know I am correct because I used deductive inferring to move from the question to the answer – deductive inferring is foolproof, isn't it?' This would be the case were the above definition correct. I will argue that it impossible to *knowingly* use deductive inferring and that, therefore this definition of deductive inferring is flawed.

Consider a deduction regarding Newton's first law of motion:

> *If an object is moving at constant velocity, then the net force on the object is zero. This object is moving at constant velocity, therefore the net forces acting on it is zero.*

This follows the syllogism:

P1: If P then Q
P2: P
C: Q

In such a syllogism, one is logically constrained to accept the conclusion if one accepts the premises. It does not matter what P and Q are, it is the structure of the argument that is important. This suggests that if people consciously use deduction to reach conclusions from true premises, then the conclusions will be true and known to be true. Another way of putting this is: it is thought that it is inevitable that a rational person who knows that P1 and P2 are true, would conclude C.

Reif (2008) agrees with this description. He says that in deductive or strict inferring 'the implied knowledge is necessarily true … Strict (or deductive) inferences are implemented by careful logical reasoning and lead reliably to correct conclusions (if the starting premises are true)' (p. 110).

These syllogisms, nevertheless, are not the descriptions of *mental activity* that they purport to be. The description of a mental activity surely requires the use of mental terms such as 'belief'. Therefore, I will consider the mental activity that occurs as someone 'thinks through' such a syllogism.

Consider again the first law syllogism rewritten in terms of beliefs:

> *Jane believed that '1: If an object is moving at constant velocity, then the net force on the object is zero.' and she believed that '2: The object is moving at a constant velocity'. She inferred that '3: The net force on the object is zero'.*

In contrast to a normal valid syllogism, it is not necessarily the case that, in Jane believing 1 and 2, she comes to believe 3. It seems possible for Jane to believe 1 and 2 and yet not form belief 3. Whether a 'correct' inference is made depends on the mind that is inferring. The laws of logic set out the conclusions we *should* make, rather than the process we *actually* use to move from premises to a conclusion.

A counterargument to this scepticism is that people can deductively infer because they know the rules (laws) associated with this process. That is, if a thinker knows how to infer deductively, and is aware of when they are using this process, they can reach conclusions that they know to be true. The following section gives us reason to doubt the existence of this 'inner awareness' of correct inferring.

5.5 Solitary rule-following

Wittgenstein (1992) gave convincing arguments for the impossibility of such solitary rule-following. He recognised the crucial role a community has in rendering any rules meaningful. For example, rules about the use of words require a community. A person living completely alone could apply the word 'chair' to a stool, and, not receiving the opprobrium of others, may continue to do so. In a community, approval and disapproval of our word usage determines their 'correct' usage. Pears (1991) discusses the impossibility of grasping the meaning of a word via a limited number of examples. He says that Wittgenstein was aware that people often do have the experience of feeling that they have suddenly understood a word (and feeling that it is fully understood), but Wittgenstein believed that these feelings were unjustified: 'these flashes of understanding cannot anticipate all the correct uses of the word. Nothing can completely prefigure practice' (p. 278).

Whenever we are using an unfamiliar word, we try it out in a certain context and see whether it is accepted or not. There is no guarantee that one's use of any word, at any time, will be accepted by a community.

Similarly, following a mathematical or logical rule is open to the same issues. Wittgenstein (1992) wonders whether it is inevitable that someone who was asked to continue the series of numbers 2, 4, 6, 8 would consistently increase each number by 2. He concludes that it is not inevitable, as a rule given in a particular form (and it would always be given in a particular form) does not and cannot determine a particular interpretation of that rule.

There are an infinite number of patterns that could begin with 2, 4, 6, 8:

> This was our paradox: no course of action could be determined by a rule, because every course of action can be made out to accord with the rule. The answer was: if everything can be made out to accord with the rule, then it can also be made out to conflict with it. And so there would be neither accord nor conflict here. (Wittgenstein, 1992, Section 201)

If there is an attempt to delineate the rule further, Wittgenstein (1992) suggests that this still results in uncertainty:

> So when you gave the Order … you meant that he was to write 1002 after 1000 — and did you also mean that he should write 1868 after 1866, and 100036 after 100034, and so on — an infinite number of such propositions? (Section 186)

To which an instructor might reply: ‘No: what I meant was, that he should write the next but one number after every number that he wrote; and from this all those propositions follow in turn’ (Section 186).

Wittgenstein then says: ‘But that is just what is in question: what, at any stage, does follow from that sentence. Or, again, what, at any stage we are to call "being in accord" with that sentence’ (Section 186).

There is no way of stating a rule that does not allow interpretation to occur. Therefore, the criterion of correctness is not that you *are* following the rule, it is whether or not you are *believed* to be following the rule. When you attempt to follow a rule in public, the community decides whether or not your attempt has been successful. This feedback may help you ‘understand the rule’, by showing what is allowed and what is not, but Wittgenstein is suggesting that it is impossible to truly understand a rule, since that would require knowledge of an infinite number of propositions. There is always a possibility of a ‘mistake’[5] in the future.

However, if thinking is not voiced in public (because it is occurring in an examination), how would someone know that they are thinking ‘correctly’? As we saw above, feeling certain of something is not a reliable indicator of truth, so one could not know absolutely that they are

[5] *By ‘mistake’, I mean a move that receives disapproval by the community.*

following the rule correctly. Similarly, we can feel certain that we are following a thinking rule (such as deductive inferring) correctly and yet not be following it. It is logically possible for a person to believe that they have carried out deductive inferring from true premises and yet a false conclusion be reached. It appears that the thesis that deductive inferring reliably generates true conclusions cannot be sustained.

It, therefore, appears possible for someone to strongly believe the premises of a syllogism and yet not draw the 'appropriate' conclusion. For example, it is logically possible for someone to read in a question that an object is moving at a constant velocity and believe that they are deductively inferring from this and their knowledge of Newton's first law, and yet not reach the conclusion that the net force on the object is zero. They could have all the feelings associated with deductive inferring and feel certain, and yet be incorrect.

Because of this possibility, I suggest that it is impossible to know that you are inferring deductively until the result of this deduction is verified. The truth-status of a belief generated by inferring (and therefore the validity of that inferring) is unknown at the time the inferring occurs. This uncertainty is intrinsic to the nature of inferring. Whether or not the inferring is valid is only determined when the new belief is tested against reality, or, in the case of a hypothetical physics question, against the agreed-upon answers. This is the case even when the premises of the deduction are known to be true rather than merely being believed. If someone does come to the concluding belief that Socrates was mortal, they cannot *know* that they have inferred correctly until they are given some other evidence that that he was in fact mortal (for instance discovering that Socrates died in 399 BCE).

The above discussion shows that logic's attempt to capture thinking has failed in a crucial aspect. It sets out how we *should* think rather than how we *do* think. It may be true that, in a syllogism, the premises imply the conclusion. However, *believing* the premises does not guarantee that you will *believe* the 'correct' conclusion.

Inferring is a mental act, where we 'move' from one belief to another whereas implication is a relationship between states of affairs. For instance, we may say that the existence of footprints implies that someone walked by earlier. In implication, there is no suggestion that a thinker is involved – it is a statement about a relationship between two facets of the world. (The question of whether implication is a feature of the 'external' world or not cannot be answered fully here.

Suffice to say that it appears possible that what we mean by 'imply' is 'able to be inferred' – that inferring is the fundamental process).

This is an important distinction as, though we may say that implication is sometimes *necessary*, it is doubtful that we can say the same about inferring – we cannot pre-empt that, because a conclusion is *logically* necessary, a certain person will find it *psychologically* necessary. Lonergan (1990) agrees with this distinction between inferring and implying. The connection between beliefs and conclusions in an instance of inferring is intrinsic to the thinker and there can be no logically necessary connection between beliefs, only psychological necessity. The patterns of necessity in implication and inferring may be similar to each other, but they are clearly different types of necessity.

The conclusion to be drawn from this analysis, and the key finding of Wittgenstein's (1992) *Philosophical Investigation*, is that the beliefs arising from deductive inferring can never be known to be true, at least not until some later time. We may feel certain, but these feelings are not bound to the *actual* truth of the beliefs. Inferring, even deductive inferring, produces merely belief, not truth or knowledge.

I will now consider the epistemological status of inductive inferring.

5.6 Inductive inferring

As detailed in the Literature Review, the conclusions reached in inductive inferring are not necessitated by the premises. Consequently, we can say that if deductive inferring does not guarantee truth, then inductive inferring will definitely not guarantee it.

The status of inductive inferring as a weaker form can be explained by referring to the logical fallacy of 'affirming the consequent'. A well-accepted logical syllogism is 'Affirming the antecedent'. This occurs when the first proposition in a conditional premise is affirmed. For example:

P1: If P, then Q
<u>*P2: P*</u>
C: Q

However, the following syllogism (affirming the consequent) is thought to be a logical fallacy:

P1: If P, then Q
P2: Q
C: P

'If P, then Q' says that if P is true, then Q must also be true. However, 'if P, then Q' does not specify whether or not Q can be true without P being true. To illustrate this, consider the following conditional:

If it rains, then the path will get wet.

On its own, this statement allows for the possibility of the path becoming wet by other means (for example by being hosed down). It follows that the path being wet (consequent) does not allow us to conclude with certainty that it has been raining – this would be fallacious reasoning (reasoning that *seems* valid but is not).

Many of the inductions we make are of this type. We know the laws governing a cause-and-effect situation and inappropriately infer the cause from the effect, such as the cause of rain from the effect of the path being wet. I acknowledge that, in many cases, we may say that the presence of an effect makes the presence of a particular cause *probable*. However, there is a clear difference between the certainty of deductive inferring (when used correctly) and the dubitability of inductive inferring.

5.7 Conclusions about the epistemological status of inferring

In conclusion, inferring produces beliefs, with which there will be feelings of confidence or even certainty associated. However, when done privately, it does not result in something that is known to be true, even when carried out 'deductively'. Truth or falsity (or something in between) will come at a later time – whether seconds or years later. If I infer from the sound of footsteps that a particular person is walking by, this belief is only verified when I see that person.

It appears, then, that the common method of distinguishing between modes of inferring may be flawed. Deductive inferring was thought to involve conclusions that were guaranteed to be true (given true premises) whereas other modes did not give such assurances. However, there is no guarantee that humans will use deduction correctly and, even if they do, they cannot know, without other observations or affirmations from others, that the conclusions they reach are true.

Truth should never have been used as the marker of deductive inferring, since believing occurs in a person's mind (where inferring occurs) while truth is independent of the mind. A better way to differentiate between different modes of inferring may be to consider the phenomenology of each type – what occurs mentally when inferring.

5.8 Implications for thinking in physics

These conclusions have implications for the investigation of inferring while 'doing' physics. In a test or examination situation, there can be no attempted falsification of a belief (for example, by checking the answers in the back of the book) and so the student remains in a state of ignorance about the correctness of the inferring. Therefore, the identification of inferring as 'deductive' cannot, therefore, be made. Instead, I will classify thinking that appears to be an attempt to use deductive inferring as *deductive-like.*

In addition to this limitation, a student, in attempting to use deductive-like inferring, may commit a logical fallacy, such as affirming the consequent (mentioned above). Any test or examination involves many instances of inferring that are not verified immediately and yet success in a physics examination is heavily reliant on such thinking abilities. In contrast, in a classroom environment there are many influences on any inferring that occurs. For example, a teacher may scaffold a problem solution and then give hints as the student progresses.

It is worth emphasising again that *believing* that you have got a question correct is very different state of affairs to that of *getting* it correct. You may believe that you read the question carefully, perhaps underlining or highlighting important information. You may also believe that you carried out the procedure carefully, entered calculations into a calculator accurately and carried out appropriate checks. Nevertheless, there can be no absolute guarantee of the answer's correctness. Checks that a student carries out may increase their confidence in their answer, but the fact that a check works does not necessitate that the answer is correct. (Following the rules of checking can be subjected to the same Wittgensteinian criticism as other thinking rules).

The unique and private nature of examination thinking made it the obvious candidate for study in the empirical component of this work.

5.9 Summary

The first research question was:

> *What is logical deduction? How is it different from other thinking processes?*

The answer to this is that the thinking process that was referred to as logical deduction is better described as deductive-like inferring. As a thinking process, it is a physical process of a person's brain. In terms of conscious experience, it is where a new belief is formed from prior beliefs by attempting to use a thinking rule that emulates implication. It is usually accompanied by feelings of certainty in the new belief that is formed, however the truth of the matter is not known until a later time. Deductive-like inferring can possibly be distinguished from other thinking processes, such as inductive-like inferring, by considering the nature of, and the connections between, the beliefs involved in the process.

6. Results and Analysis 2: Empirical Investigation

The aim of this component of the research was to discern some of the modes of thinking that occur while solving physics questions and determine the role, if any, of deductive-like inferring. The thinking involved in solving physics examination questions was verbalised and so the thinking is represented by the transcripts of the verbalisations. An analysis of these transcripts, written answers and videos facilitated the classification of this thinking.

It is important to note that none of this data is thinking as such. The verbalisations were a conscious attempt to state the thinking that was occurring, but they are merely representations of the thinking. An analogy of this is the description of a scene or an event given over the telephone. The describer, inevitably, cannot fully describe the scene but will highlight those things deemed as important by them.

6.1 Identification of inferring episodes

The aim of the first part of the analysis was to identify episodes of inferring. That is, to identify when the thinker was able to reach a conclusion from other beliefs. Hence, there was a requirement to identify both the conclusions (which I will refer to as conclusion-beliefs) and the associated preceding beliefs (which I will refer to as premise-beliefs). These were both given as propositions, for example ‘the current goes from positive to negative’.

It was relatively easy to identify these because the conclusions were often preceded (sometimes followed) by a term that suggests inferring. These include ‘so’, ‘therefore’ and ‘that means’. When the term followed the conclusion-belief, a common term was ‘because’. There were usually multiple conclusion-beliefs in each verbalisation, and these were often used as premise-beliefs in a following part, forming what is usually referred to as a chain of reasoning. Here I will refer to it as a chain of inferring.

A very obvious hint that a conclusion was reached was that the question was answered. That is, the statement of the answer is the final conclusion-belief in the question-answering episode. Nevertheless, in several of the questions, a more important conclusion-belief was where the thinker discovered the appropriate method to carry out the calculation. The thinking that followed this was merely ‘plugging’ numbers into a formula. In the videos, this was exhibited in the quicker pace in completing this part of the question.

In considering the verbalisations, it is worth remembering that the answers were not known to be correct, regardless of how much confidence was expressed. I therefore take it that much of what is said during the verbalisations, and everything written or drawn on the examination, are to be classified as beliefs. The only statements that could be taken as unquestionable are those where the information given in the question was read out or paraphrased. The answers to the questions, unverified at the time of being verbalised, can only be beliefs.

An example of the question-and-answer sheet, and part of the corresponding verbalisation are shown in Figures 3 and 4 below.

Question 3 (5 marks)

Figure 3 shows a simple DC motor consisting of a square loop of wire of side 10 cm and 10 turns, a magnetic field of strength 2.0×10^{-3} T, and a commutator connected to a 12 V battery. The current in the loop is 2.0 A.

10cm
0.1 m

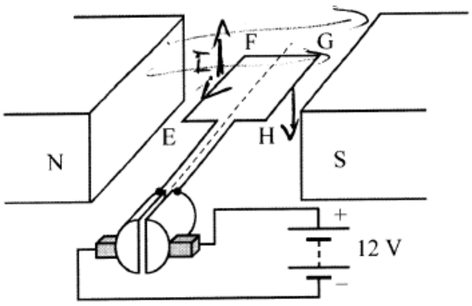


Figure 3

a. Calculate the magnitude of the total force acting on the side EF when the loop is in the position shown in Figure 3. Show your working. 2 marks

$F = nBIl = 10 \times 2.0 \times 10^{-3} \times 2.0 \times 0.1$

$= 4.0 \times 10^{-3}$ N

$\boxed{4.0 \times 10^{-3} \text{ N}}$

Figure 3 (Image: VCAA, 2019)

Verbalisation:

'A) calculate the magnitude of the total force acting on the side EF when the loop is in the position shown in figure 3 and show your working'. So this is a pretty standard question about the force on a wire in a magnetic field and we see that side EF is in fact at right angles to the to the field and we can get the current direction just it may not come up in the actual analysis but we can we know the current goes from positive to negative so the current would be going from F to E, and we can see that the field is actually going across like that (thinker gestures with pen) *so the current is perpendicular to the field, and that means that the force is at its maximum value and is given by F =NBIl where N is the number of turns which is 10, the field strength is 2 by 10 to the negative three Tesla, current is 2 amps and the length in metres, so point one sorry 10 centimetres is 0.1 of the metre and so we needed it in metres and we could probably do that in our head so those two cancel each other out and we've got 2 times 2 so equals 4 by 10 to the negative 3 newtons and that's the correct number of significant figures then we can put that in the in the box*

Figure 4

One can see in this transcript the thoughts that would not normally have been expressed aloud while completing such a question. There is thinking about the general nature of the question ('this is a pretty standard question') as well as thoughts that are specifically aimed at reaching an answer (‘the current is perpendicular to the field, and that means that the force is at its maximum value’). Consequently, the chain of inferring that occurred in the mind of the thinker can be postulated.

An example of an inferring episode in this verbalisation is:

the current goes from positive to negative so the current would be going from F to E

The structure of this is:
Premise-belief (PB): *the current goes from positive to negative*
Inferring term: *so*
Conclusion-belief (CB): *the current would be going from F to E*

This analysis makes the inferring process clear – how the thinker perceives a causal connection between holding the premise-beliefs (some of which may not have been stated) and ‘coming to’ the conclusion-belief.

The next episode uses the previous CB as a PB:

the current would be going from F to E, and we can see that the field is actually going across like that ***so*** *the current is perpendicular to the field*

Here there are two PBs stated, shown by the use of the word ‘and’, leading to the CB. In the analysis, only the propositional content was considered. So, in this example, the word ‘would’ is changed to ‘is’, and ‘we can see’ and ‘actually’ are ignored.

The inferring is, therefore, simplified to:

The current is going from F to E and the field is going across like that, ***so*** *the current is perpendicular to the field.*

6.2 Analysis Steps

In spoken and written language, inferring is signified by a range of terms, including ‘so’, ‘that means’, ‘therefore’, ‘since’ and ‘because’. Kushiroa, Ogata and Aoyama (2021) suggest the following as well: ‘even so’, ‘in the case’, ‘then’, ‘when’, ‘as’ and ‘after’. The thinking shown in verbalisations was scanned for inferring terms and the beliefs connected to these.

The steps in the first phase of the analysis were, therefore, as follows:

1. Identify propositions in the transcript – these are construed as beliefs.
2. Identify terms signifying inferring – such as ‘so’, ‘that means’, ‘because’ and ‘therefore”
3. Identify the beliefs that are linked by these terms.
4. From these identify the prior beliefs, that I have termed ‘premise-beliefs’, and identify the ‘conclusion-beliefs’ in each episode of inferring.

It was assumed that any proposition read out in the questions was a premise-belief. This relies on the assumption that the thinker understood the question perfectly, which of course may not be the case.

6.3 Analysis example

As suggested earlier, the thinking is in two parts: the first is leading up to establishing which formula to use and the second is applying this formula. I have, therefore, broken this transcript into those parts. As the second part is more straightforward, I have focussed on the first part. This pattern is repeated in several of the questions. I have then identified the inferring terms and propositions by capitalising and bolding them respectively.

Question 3. ‘Figure 3 shows a simple DC motor consisting of a square loop of wire of side 10 centimetre and ten turns, a magnetic field strength of two by 10 to the negative 3 Tesla and a commutator connected to a 12 Volt battery the current in a loop is 2 amps’. (Reading the information in the question)

*NOW I'M PRETTY SURE **the 12 volts may not be relevant***
*SINCE **we've been given the current***
***we won't really need to worry about the 12 Volts**,*
*SO **that's a bit of a distractor**.*

SO we see there ***the loop joined to this time a split ring commutator rather than the slip rings as you would want for a DC motor****.*

*'****a) calculate the magnitude of the total force acting on the side EF when the loop is in the position shown in figure 3 and show your working'****.*

so ***this is a pretty standard question about the force on a wire in a magnetic field***

and we see that ***side EF is in fact at right angles to the to the field***

and ***we can get the current direction***

just ***it may not come up in the in the actual analysis***

but we can ***we know the current goes from positive to negative***

SO ***the current would be going from F to E****,*

and we can see that ***the field is actually going across like that (Annotation of diagram – current direction and field direction shown)***

SO that ***the current is perpendicular to the field****,*

and THAT MEANS that ***the force is at its maximum value and is given by F =NBIl***

6.4 Re-writing in terms of belief

The propositions shown here are stated as matters of fact, but they are 'merely' beliefs that the thinker held. As discussed earlier, it is important to distinguish between implication and inference, so, to make this distinction clear here, I will add 'believe' to each of the propositions. This gives greater epistemological accuracy.

For example:

1. ***I believe that current goes from positive to negative*** *SO* ***I believe that the current would be going from F to E.***

2. ***I believe that the current is going from F to E and I believe that the field is actually going across like that*** *SO* ***I believe the current is perpendicular to the field***

3. ***I believe the current is perpendicular to the field*** *and THAT MEANS that* ***I believe that the force is at its maximum value and is given by F =NBIl***

In each of these cases, the premise-beliefs are given first, followed by the inferring term and then the conclusion-belief. Also note that the conclusion for 1 is also one of the premise-beliefs for 2 and the conclusion-belief for 2 is also the premise-belief for 3. These three episodes, therefore, form a chain of inferring.

This is a more accurate rendering of the thinking and makes it clear that the conclusion-beliefs do not follow inevitably from the premise-beliefs. For instance, it is possible for someone to believe that the current travels from positive to negative and yet not believe that the current passes from F to E in the diagram. These cannot, therefore, be instances of deductive inferring per se.

This analysis was carried out on all the transcripts. Another example is shown in Figures 5 and 6.

Question 5 (8 marks)

Students conduct an experiment in which a mass of 2.0 kg is suspended from a spring with spring constant $k = 100\ \mathrm{N\ m^{-1}}$.

Ignore the mass of the spring.

Take the gravitational field, g, to be $10\ \mathrm{N\ kg^{-1}}$.

Take the zero of gravitational potential energy when the mass is at its lowest point.

The experimental arrangement is shown in Figure 6.

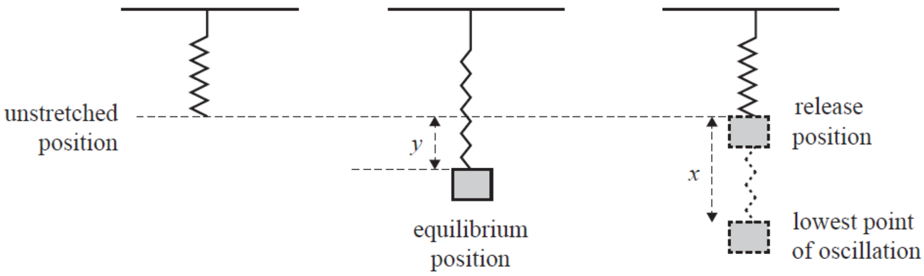


Figure 6

a. The mass is attached to the spring and slowly lowered to its equilibrium position.

Calculate the extension, y, of the spring from its unstretched position to its equilibrium position. Show your working. 2 marks

Figure 5 (Image: VCAA, 2019)

And the corresponding transcript:

Question 5. 'Students conduct an experiment in which a mass of two kilograms is suspended from a spring with spring constant k equals1000 newtons per metre. Ignore the mass of the spring.' and that's pretty standard. 'Take the gravitational field, g, to be 10 units per kilogram.' OK so not the normal 9.8 that's interesting. 'Take the zero of gravitational potential energy when the mass is at its lowest point.' So looking at the diagram they're talking about here. 'The experimental arrangement is shown in figure 6.' OK so we see what the spring would be like without attaching a mass. When a mass is attached it goes to here right that's the equilibrium position, and if it's released from this position it will oscillate. Says 'The mass is attached to the spring and slowly lowered to its equilibrium position.' OK so the equilibrium position here is the one where the forces are balanced. OK so another way of saying that is that the net force is 0. 'a) Calculate the extension y of the spring from its unstretched position to its equilibrium position.' OK so if we use the idea that the gravitational force is equal to the spring force we should be able to make some progress. So the force due to gravity is equal to mg and the force due to the spring is equal to kΔx. In this context... well and we can say if F-g equals F-s therefore the mass, 2, times 10 OK equals - because we've been told to use 10 newtons per kilogram -equals the spring constant, is 100 times - now we use the symbols that they've used - so 100 times y. So that's 20 = 100 times y, that gives us y = 0.2 so we can put 0.2 metres in there. OK.

Figure 6

The major inferring episodes are:

1. ***I believe the equilibrium position here (PB)*** *IS* ***the one where the forces are balanced (CB)***

2. ***I believe the forces are balanced (PB), I believe if we use the idea that the gravitational force is equal to the spring force we should be able to make some progress (CB)***

3. ***I believe if we use the idea that the gravitational force is equal to the spring force we should be able to make some progress (PB), I believe the force due to gravity is equal to mg and the force due to the spring is equal to k∆x (PB),*** *WE CAN SAY* ***I believe F-g equals F-s (CB)***

As all quantities except Δx are known, the equation $mg = k\Delta x$ is able to be rearranged and solved. Note that in episode 2, there is no inferring term.

The structure of these episodes strongly suggests that inferring is occurring. The thinker is moving from previously-established beliefs to new beliefs each time. It is clear that they firmly believe that the premise-beliefs led to the conclusion-belief in each case. This is evidenced by the use of words such as ‘so’ and ‘must’. They also have confidence in the answers – there is no use of the words ‘probably’ or ‘’possibly’ in these inferring episodes. This suggests the thinker has feelings of certainty about these beliefs. This does not, however, mean that the conclusion-beliefs we known to be correct – this is impossible in an examination situation.

6.5 What type of inferring?

The transcripts do show that inferring was occurring but this was not deductive inferring, in the traditional sense. This is because, as established in the previous chapter, true deductive inferring would require that the thinker *knowingly* use laws of deductive inferring, and this is impossible for private thinking.

Instead, appropriate questions to ask are: Is the inferring deductive-like or inductive-like?; and: Are there grounds for believing that there was an *attempt* to use deductive inferring? To determine whether this is the case, the episodes of inferring need to be further scrutinised. If it is the case that the propositions that form the premise-beliefs imply the conclusions, this is evidence, though not conclusive, of deductive-like inferring.

Consider the first set of episodes shown above:

1. ***I believe that current goes from positive to negative*** *SO* ***I believe that the current would be going from F to E.***

2. ***I believe that the current is going from F to E and I believe that the field is actually going across like that so I believe the current is perpendicular to the field***

3. ***I believe the current is perpendicular to the field*** *and THAT MEANS that* ***I believe that the force is at its maximum value and is given by F =NBIl***

By removing the 'believe', these are transformed to:

1. ***The current goes from positive to negative*** *SO* ***the current would be going from F to E***

2. ***The current is going from F to E and the field is actually going across like that*** *SO* ***the current is perpendicular to the field***

3. ***The current is perpendicular to the field*** *and THAT MEANS that* ***the force is at its maximum value and is given by F =NBIl***

Each can then be written as a syllogism:

1.

<u>P1: The current goes from positive to negative</u>

C: The current is going from F to E

2.

P1: The current is going from F to E

<u>P2: The field is actually going across like that</u>

C: the current is perpendicular to the field

3.

<u>P1: The current is perpendicular to the field</u>

The force is at its maximum value and is given by F =NBIl

Of these, only episode 2 is valid. This can be seen in the diagram drawn when the question was answered (Figure 7):

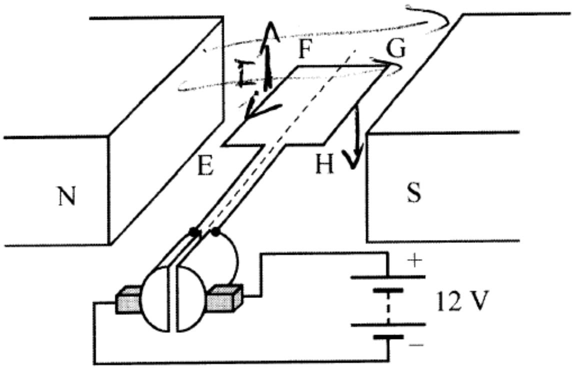


Figure 7

It shows the current flowing from F to E and the magnetic field lines (drawn in) pointing from North to South. Given the perspective conventions of such a diagram, the current is perpendicular to the field.

Does the lack of validity for the other two episodes mean that another form of inferring, such as inductive-like inferring is being used? There is no evidence to suggest this, since inductive syllogisms also usually have at least two premises, as we have seen:

P1: Every swan I have ever seen is white
<u>P2: Peter has a swan</u>
C: Peter's swan is white

In episodes 1 and 3, there appears to be the same confidence in the conclusion-beliefs as expressed in 2. It is probable that there was another premise-belief/knowledge held by the thinker that allowed the conclusion – a hidden premise-belief.

In episode 1, the belief may have been:

If the current is from positive to negative, then it travels through the split ring, then through the loop in the order HGFE.

P1: The current goes from positive to negative

P2: If the current is from positive to negative, then it travels through the split ring, then <u>through the loop in the order HGFE.</u>

C: The current would be going from F to E

This is now valid.

In episode 3, the thinker may have drawn on a general physics principle that:

When a side of a coil is perpendicular to the magnetic field, the force is at its maximum value and is given by $F = NBIl$

So the syllogism becomes:

P1: When a current is perpendicular to the magnetic field, the force is at its maximum value and is given by $F = NBIl$

<u>*P2: The current is perpendicular to the field*</u>

The force is at its maximum value and is given by $F = NBIl$

This is also valid – it is modus ponens or affirming the antecedent. Written in general form:

P1: If P, then Q

<u>*P2: P*</u>

C: Q

Each question was analysed in the same, systematic manner. The steps of the second phase of the analysis were:

1. *The major inferring episodes were re-written as 'syllogisms' in terms of premise-beliefs and conclusion beliefs.*
2. *'Syllogisms' were re-written as proper syllogisms by removing the reference to belief.*
3. *Hidden premises (premise-beliefs) were added where appropriate.*
4. *The syllogisms were analysed for validity (they were compared to formulaic syllogisms)*
5. *If valid, it was concluded that deductive-like inferring was employed.*

In many cases, the hidden premise-belief was a law of physics, or a formula. Once added, the syllogisms were much improved. The alternative is to believe that the thinker came to the conclusion in a partly mysterious way – that new beliefs arose from an unknown cause. However, it was not the case that every syllogism had missing premises, and many had the general laws of physics and the specific information in the question stated, such that the evidence of deductive-like inferring is strong. Also, when the transcript of a whole question is considered, the evidence of deductive-like inferring is also strong.

It may seem odd in the above analysis that the idea of belief was added only to be removed again. This was done as it was initially important to emphasise that the statements were statements of belief and not facts. They were then removed to analyse the episode as deductions so that their validity could be accurately assessed.

This analysis was carried out systematically on all the transcripts and a series of syllogisms was discovered in each. These syllogisms were found to be deductively valid, and, so, the thinking was determined to be deductive-like inferring.

Consider the following question (Question 4) and transcript:

Calculate the RMS power loss in the connecting wires for this new situation. Show your working.

So again we think that power loss equals I squared R, we know the resistance is 40 ohms from the previous page as they're the same wires but we don't know the current OK it says that it is an 8 to one step down transformer. If the voltage is being stepped down then that actually means that the current is being stepped up, so the current and we can write this as a mathematical relationship that that I-primary on I-secondary equals N-secondary over N-primary and we know I secondary already because we know that the light globe in order for it to operate at 240 volts and 480 watts, that the current has to be 2 amps OK so we can now put in that I secondary is 2 amps and that ratio NS to NP is actually 1 / 8 from the information there so IP equals 2 / 8 = .25 amps now we can you use P-loss equals I squared R equals .25 squared times resistance which is 40 equals 0.0625 times 40 (uses calculator) 0.0625 times 40 = 2.5 Watts so we see that the power loss which had been 160 Watts has been reduced to 2.5 watts, simply by using this different arrangement

Figure 8

I believe that there are six key 'deductions' made in reaching the answer to this question and together these form a chain of inferring. I have shown these as syllogisms below (without using 'P1', 'P2' … and 'C'), writing each belief as a proposition. Hidden premises are shown in brackets.

Applying the known formula

Requirement to calculate Power Loss

Power loss = I^2R (so I and R are required)

<u>R is known but the I is not</u>

so I will have to be determined

Calculation of current

The current is given by the relationship $\frac{I_p}{I_s} = \frac{N_s}{N_p}$

<u>(I_p is the current we need to calculate)</u>

(so need values for I_s and $\frac{N_s}{N_p}$.)

Determination of I_s

(need values for I_s)

<u>The globe is still operating at 240 volts and 480 watts.</u>

I_s is still 2A (*this was calculated in an earlier question*)

Determination of $\frac{N_s}{N_p}$

(need values for $\frac{N_s}{N_p}$)

$\frac{N_p}{N_s}$ is given in the question stem as 8:1

$\frac{N_s}{N_p} = \frac{1}{8}$

Determination of I_p

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

$I_s = 2\ A$

$\frac{N_s}{N_p} = \frac{1}{8}$

$$\frac{I_p}{2} = \frac{1}{8}$$

$$I_p = \frac{2}{8} = 0.25A$$

Determination of power loss

$P_{loss} = I^2R$

<u>I = 0.25 A and R = 40 Ω</u>

$P = 0.25^2 \times 40 = 2.5$ W (ANSWER)

In this chain of inferring there were only two premise-beliefs/conclusion-beliefs not given and all the syllogisms appear to be valid. It is clear that deductive-like inferring has been the key mode of thinking in answering this question. Also, it is difficult to see how it could be tackled in another way.

There is little doubt that the conclusions in each question did follow logically from the premises. However, this does not mean that deductive inferring *per se* was employed to reach the conclusion. Instead, the thinking employed is better termed deductive-like inferring. I conclude that part of the logical thinking used in the physics problem-solving by the subject is deductive-like inferring and, further, that it strongly suggests that a student's ability to carry out this type of thinking will be an important factor in their success, or otherwise, in studying physics.

6.6 The role of inductive-like inferring

Inductive-like inferring did have a part to play as well, particular in determining one's approach to a question. For instance, in the transcript of Question 3 shown earlier, one of the statements was '*Now I'm pretty sure the 12 volts may not be relevant'*. 'Pretty sure' suggests a lack of the certainty that accompanies inductive-like inferring – the thinker is admitting the possibility of it being relevant. Such beliefs are likely based on previous experience of similar questions and the fact that examiners can include information that is not required to reach a solution.

Another example from the same question is '*so this is a pretty standard question about the force on a wire in a magnetic field'.* The belief that it is a standard question can only come about by mentally comparing the question with similar questions seen in the past.

Other beliefs established via inductive-like inferring are specific strategies for answering the question. In Question 3, the strategy might be 'in questions like this, the force is either zero or given by F=NBIl, depending on whether the wire is parallel or perpendicular to the field – so I need to see what the orientation of the wire and the field is'.

6.7 Summary

The second research question was:

> *What type thinking occurs when answering physics questions in an examination context? What is the role of logical deduction in this thinking?*

The results indicate that an important thinking skill that occurs in examination physics problem solving is deductive-like inferring and that inductive-like inferring plays a more minor role. Deductive-like inferring is the key skill involved in 'moving' from the information given in the question, and remembered physics knowledge, to a solution. Inductive-like inferring is involved in guiding the thinker to an appropriate method of solution.

A further conclusion from the empirical component of the research is the utility of the think-aloud method in revealing the thinking that occurs while 'doing' physics examination questions. This affirms the findings of other studies (for example Reinhart et al., 2020) that show this to be an effective method of making thinking visible.

7. Discussion

The findings of this research have several implications for high school physics education and education in general. As well, it provides a foundation for further investigations into the logical thinking involved in ‘doing’ physics. This discussion considers the significance of the results in the two parts of the research and serves to answer the third research question:

Should logical deduction be taught more explicitly in physics classes?

7.1 Philosophical investigation

The principal outcome of the Philosophical Investigation was a redefinition of logical deduction – one that was a radical departure from existing definitions. Traditionally, the nature of logical deduction implied that if a person infers deductively from true premises, they will inevitably come to a conclusion they could accept as true. That is, deductive inferring appeared to come with a ‘truth guarantee’. For instance, Baserer (2020) stated that deductive inferring is usually differentiated from inductive inferring by referring to the certainty of the conclusions, while Reif (2008) says that in deductive or strict inferring ‘the implied knowledge is necessarily true’ and that ‘strict (or deductive) inferences are implemented by careful logical reasoning and lead reliably to correct conclusions (if the starting premises are true)’ (p. 110).

This research has shown that we should not have such confidence in deductive inferring. When inferring privately a person is attempting to follow a logical rule. However, as Wittgenstein (1992) shows, there is no guarantee that the person follows this rule, despite the fact that they may believe that they are. If there is no guarantee that they have used the rule correctly, then there is no guarantee that the conclusion-belief is true. Also, verification of the truth or correctness of the conclusion-belief, and therefore of the correctness of the rule following, comes some time after the inferring has occurred. Until this occurs, the correctness of the inferring is unknown.

The same issue was found to be the case for inductive inferring – an attempt to use it may not be successful. Given that this mode is already agreed to not have a guarantee of truth, and has conclusion-beliefs that are, at best, probable, the added issue of rule-following renders any conclusion-beliefs less probable and, sometimes, impossible.

Consequently, it was determined that the terms ‘deductive’ and ‘inductive’ were misleading. I proposed that the terms ‘deductive-like’ and ‘inductive-like’ be used instead. Deductive-like inferring is an attempt at inferring in a deductive manner. It is distinct from a valid logical syllogism where a set of premises necessitates a certain conclusion, as there is no necessity to the inferring process.

These outcomes have significant consequences for discussions regarding reasoning in educational contexts. Whenever a student is working alone on a question that involves inferring, they are forming new beliefs about a situation (hypothetical or real). These new beliefs cannot be completely verified until they find out the answers. I say ‘completely verified’ since they may be checked for consistency with each other and the original beliefs in cross-checks. To form the new beliefs, the student will attempt to use a series of thinking rules that are, potentially, unique to that person. There is no way that the student can know, at the time of using them, that the rules are ‘correct’ or if they have used them correctly. I am not recommending that students have an epistemological crisis every time they solve a problem. Nevertheless, I am suggesting that they proceed with more caution than they otherwise would. Furthermore, to increase the likelihood of success, instruction in the nature of this thinking and practice of it is appropriate (this will be explored more in a later section). If thinking is to be at the centre of education (as I believe it should), many teachers will need more instruction in philosophy – particularly epistemology and logic.

The Philosophical Investigation has also helped to clarify the distinction between the ideals of deductive logic and the real thinking (inferring) that occurs in the minds of humans. The importance of an understanding of the nature of belief in this distinction cannot be overstated. Therefore, for educators to appreciate the distinction, it is imperative that they too have an understanding of belief and associated epistemological concepts. As well, to understand the distinction between logical deduction and deductive-like inferring[6], teachers would first need to understand what each of these is.

Programs that aim to improve thinking would be enhanced by the formulation of ‘logical’ thinking given above. For example, the efforts of Project Zero (see Ritchhart et al., 2011) would be complemented by it. They advocate making thinking visible as a means to improving it. Recognising different types of thinking in student work is difficult without a good knowledge of

[6] *They should also understand the distinction between inductive reasoning and inductive-like inferring.*

the different types of thinking processes. Therefore, becoming acquainted with deductive-like and inductive-like inferring would aid the recognition and, therefore, improvement of these skills. For instance, to determine whether a student is reasoning well or not (‘Reasoning with Evidence’, see Ritchhart et al., 2011, p 11), a teacher may look for evidence, in their thinking-made-visible, of deductive-like inferring. As well, a teacher might advise a student who has used inductive-like inferring that they could strengthen their thinking by using deductive-like inferring instead. Furthermore, both think-aloud transcripts and ‘normal’ problem solving steps could be analysed using the form of argument mapping used in this study.

7.2 Empirical investigation

The principal outcome of the Empirical Investigation was the identification of deductive-like and inductive-like inferring in the verbalisations of problem solving.

The motivation for exploring the nature of this thinking was to determine whether it included logical thinking (deductive-like inferring). The presence of this type of thinking would have then made it worthwhile to explore the possibility of teaching logical thinking skills to physics students. It was thought that problem-solving in physics might involve logical thinking because of the subject’s axiomatic nature, as detailed by Sneed (2012), and Viennot and Décamp (2020).

The Empirical Investigation provides evidence that deductive-like inferring is an important element of physics problem solving. The verbalisations demonstrate how the thinker was able to ‘move’ from information in the question, and their own physics knowledge, towards conclusion-beliefs that allowed the question to be answered. As well, the analysis of the verbalisations showed that these instances of inferring had the structure and language of deductive inferring, despite the fact that they were not *actually* deductive inferring. Instances of deductive-like inferring were found in all of the transcripts and appears to be integral to the problem-solving process. For example, in question 4c, there were six episodes of deductive-like inferring, in a chain of inferring, towards establishing the answer.

Another outcome was the discovery that inductive-like inferring was used in problem solving, though to a lesser extent. It was primarily used in the preliminary analysis of a question to help determine the type of question and the area of physics involved.

Though further work is required to confirm it, these findings can be tentatively generalised to student thinking in similar situations. This thinking, of course, may not always generate the correct answer, but the expectation is that it would involve *attempts* at deductive and inductive-like inferring. (As shown in the analysis of the verbalisations, this type of thinking is assumed to occur whenever a student uses one of the key 'inferring terms', such as 'so' and 'therefore'). The ability to infer is, therefore, valuable for students of physics, among other skills and knowledge.

7.3 Research question

The overall research question was: What is logical deduction, in relation to physics, and how can students improve in this? It is now possible to answer the first part of this: What is logical deduction in relation to physics?

Firstly, logical deduction, as a thinking process, is more properly termed deductive-like inferring. This is the mental process (which is a brain process) where someone comes to a new belief as a result of other beliefs that they hold. In doing this, the person attempts to follow a law of deduction, but cannot know that they have done so correctly. They can only know that they have come to the correct conclusion-belief when that belief is verified in another way.

Secondly, deductive-like inferring has been shown to be utilised, in an important way, in physics problem solving. There is no evidence, at this point, that its use in physics is different to its use in other fields. This is not a surprise, as it is widely thought that logic or logical deduction refers to *general* thought processes.

The important conclusion is that deductive-like inferring is *relevant* to physics and physics education.

7.4 Improvement of deductive-like inferring

As discussed in the Literature Review, physics is perceived as a difficult subject and educators are searching for ways to make it seem, or be, less difficult. The pervasiveness of deductive-like inferring in physics problem-solving thinking makes it likely that improvement in this skill would lead to improvements in problem solving in test and examinations. If this is the case, it is of great importance to physics teaching.

7.5 Explicit teaching and practice

It is likely that improvement in deductive-like inferring would be achieved through the methods used to teach other thinking skills: the explicit teaching of the skill followed by student practice of it. The fact that it is inherently unpredictable means that it is difficult to master, and one needs the experience of successful inferring to know how that 'feels' – the qualia of successful inferring. Of course, practice may make it more likely that you will infer correctly, and come to valid conclusion-beliefs, but it cannot make it certain.

Further empirical research is required to verify the effectiveness of explicit teaching but there is reason for hope – there is evidence that the study of logic has positive consequences for a range of subject areas (see Quintana and Schunn, 2019). It is important to note, however, that, while significant, deductive-like inferring is one skill among a range of skills, knowledge and understanding, and success in physics requires the development of all of these.

The following is an indication of the form such teaching would take, based on the findings of the Empirical Investigation. The explicit teaching could occur both within and outside the physics classroom. It would involve elements of a course in formal logic – the laws of implication. By teaching these, students would learn how they *should* infer.

Students would learn the meaning of the following terms: state of affairs, proposition, truth and falsity. As well, the difference between *general terms* (that describe categories) and *singular terms* (that identify a specific thing) and the meaning of the five *logical connectives*: 'not', 'and', 'or', 'if … then … ' and 'if and only if' (Gensler, 2012, p. 8) and the use of four other words: 'all', 'no', 'some' and 'is' (Gensler, 2012, p. 7). Then they would learn the structure of a syllogism and be able to identify those that are valid and *why* they are valid. They would come to understand that validity depends only on the structure of the deduction and the meanings of the logical terms used. Fallacious reasoning (inferring that looks deceptively reasonable) would also need to be described in detail.

It should be noted, however, that such teaching, regardless of how effective, can never guarantee that students will employ this deductive-like inferring successfully in a test or examination. There are at least two reasons for believing this. The first is that one can never know, at the time of thinking, whether or not the rule has been 'followed'. The second, related reason is the problem of induction – past instances of the successful use of a rule cannot guarantee the future successful use.

This proposal of the explicit teaching of logical deduction resonates with the findings of Connelly (1973), who determined that a student's development of logical reasoning ability is dependent on the extent of the instruction given in this.

7.6 Benefits of explicit teaching and practice

The perception of the difficulty of physics, discussed in the Literature Review, may be changed if students understand that part of physics thinking is *logical* thinking (deductive-like inferring). The Empirical Investigation revealed three 'skills' involved in physics-problem-solving thinking: knowing and understanding the nature of physical laws; applying these laws, using deductive-like inferring, to the particular situations presented in a question; and, an inductive skill, recognising which part or parts of physics a question is addressing.

An understanding of the differentiation of problem solving into these skills may assist students and teachers. Firstly, it may allow them to perceive that there is less to learn than they may have first thought – they could see that the logical thinking skills are those that are utilised in other subjects and in life outside the classroom. Secondly, the physics skills and logical skills could be targeted separately for improvement. Similarly, Sing and Marshman (2015) found that a lack of the ability in applying logic to questions caused student difficulties in physics problem solving. Having students explicitly practice such deductions could resolve these difficulties.

Angell et al. (2004) found that one of the difficulties in learning physics is that it involves multiple representations – formulae, diagrams, graphs and written descriptions. One of these representations is the list of steps used in solving a problem. With an understanding of the distinction above, students could understand that the link between many of these steps is a *logical* link rather than a physics-related link. Consequently, their perception of the amount of actual physics content would change for the better.

The explicit teaching of deductive-like inferring can also be construed as a program to improve critical thinking. However, its advantage over more general critical thinking programs is the targeting of a distinctive skill. With a narrow focus on deductive-like inferring, students could identify when they are using, or attempting to use, this type of thinking and potentially improve it. There is also considerable support for the idea that reasoning is an important component of critical thinking. For instance, Bigozzi et al. (2018) note that ‘a critical thinker needs the skills to identify what is implicit in reasoning and to judge if the basis of an inference is solid or not’ (p. 3).

Explicit instruction would mean that some of the issues with Inquiry Based Learning (IBL) are avoided. As detailed in the Literature Review, leaving students to ‘think through’ physics by themselves (by undertaking their own inquiries) has been found to be an ineffective instructional method. This is particularly the case with deductive-like inferring, given its inherently unpredictable nature. Hattie’s (2008) work gives support to the proposal of explicit teaching of logical thinking skills, as he shows that students learn theoretical topics more effectively through this teaching mode. For effective learning of deductive-like inferring to occur, the teacher needs to model the use of it to students.

The strengthening of students’ understanding of the logical relationships in physics could also be beneficial, as it could help to resolve misconceptions. For example, a well-known misconception involves Newton’s first law of motion. If an object is moving at a constant velocity, it is often assumed (incorrectly) that a net force is required to keep it moving. In actuality, the absence of a net force allows the continuation of the constant velocity. If it is reinforced to students that the constant velocity allows one to infer that the net force is zero (or that any forces acting are balanced), and they practice using this inferring process, then they would be less likely to revert to the misconception.

Another benefit would be that the reflections on thinking would constitute metacognition. This is one of the proven strategies for improving learning outcomes in physics detailed in the Literature Review (for example, see Ali et al., 2014) and when students reflect on the inferring that they use in thinking, they are implementing metacognition. Such reflection may result in the improvement of these skills, and, hence, their understanding of complex material. This is particularly valuable given the difficulty in following thinking rules that was detailed in the Philosophical Investigation. Realising that you have successfully used deductive-like inferring will be of assistance in future inferring episodes – via inductive-like inferring, you will know what it ‘feels like’ to infer in a deductive-like manner.

7.7 Think-aloud method

Another beneficial outcome of this research is the discovery of the utility of the think-aloud method for investigating deductive-like inferring in tests and examination. The benefit of this approach is that the thinking is verbalised concurrently rather than retrospectively. (Retrospective verbalisations have been shown to be inaccurate – see Hu and Gao, 2017, p. 182). A verbalisation is an example of 'making thinking visible', particularly when it is transcribed (see Ritchhart et al., 2011). When combined with the argument-mapping method used in this study, it becomes a powerful tool for analysing student thinking.

7.8 VCE Physics Study Design

Another significant outcome of this research is the support it gives for the idea that curriculum documentation, such as the VCE Study Design, should explicitly mention logical reasoning as a key thinking skill. As mentioned in the Literature Review, the current Study Design (VCAA, 2022) does have a section devoted to Critical and Creative thinking and mentions the skill of making 'reasoned predictions' (p.16). However, there is no detail regarding this skill, and it does appear that such thinking is an important element of physics thinking. A common question-type in VCE Physics examinations is the 'show' question. In such a question, a student is given the answer and is expected to give a justification for it. Consider the following example by the VCAA (2022):

> *Show that each ion has a speed of 3.16 x 10^5 m s^{-1} when it exits the cathode. Assume that the ion leaves the ion source with negligible speed. Show your working. (p. 17)*

In this question, a student is expected to present a logical argument for the speed being 3.16 x 10^5 ms^{-1}.

The 2022 VCE Physics External Assessment Report (VCAA, 2023) gives the following worked solution:

$$qV = \frac{1}{2}mv^2$$

$$1.6 \times 10^{-19} \times 1500 = 0.5 \times 4.80 \times 10^{-27} \times v^2$$

$$\Rightarrow v = 3.16 \times 10^5\ m\,s^{-1}$$

The '⇒' symbol signifies 'therefore', while the first two lines are premises showing that this solution is in the form of an argument. For a student to be successful at such a question, they would need to understand how, in general, premises can justify a conclusion. As shown in this study, other question types are also amenable to deductive-like inferring. There is good evidence that this thinking skill should be made explicit in the Study Design.

7.9 Quantum physics and logic

It is worth noting that the use of logic for physics education that has been presented is appropriate for classical physics, but it may not be for quantum physics. Quantum physics has seriously challenged our notions of exclusivity – the idea that a proposition is either true or false. It is now possible to say that a proposition is both true and false simultaneously. According to Oldofredi et al. (2022): 'As soon as Quantum Mechanics (QM) achieved a definite and coherent mathematical formulation, several physicists and philosophers claimed that its formal structure does not conform to the laws of classical propositional calculus' (p. 2). However, this does not pose a major difficulty for high school physics since the quantum content (of the Victorian course) is minimal. However, the fact that there is now a quantum logic/computing field, is another reason for physics students to have a solid grounding in logic.

7.10 Classroom research and academic research

The method I used in the empirical component of the research holds much promise for further studies on student thinking and as a method that teachers could implement in the classroom to investigate thinking.

The think-aloud and argument mapping method can be used whenever a teacher needs information about the students' thinking patterns (in physics or otherwise) and can provide valuable feedback to students and teachers. It would give students a metacognitive perspective on their own thinking and allow them to determine whether errors have been made in physics thinking or in logical thinking. Equally, it would allow teachers to perceive the areas on which they need to focus their teaching, be it physics-related or logic-related.

This study also gives motivation for further research that assesses the effectiveness of logic education on student success in physics.

7.11 Limitations

There are several factors limiting the significance of the results of this research. The philosophical investigation made various assumptions about the nature of reality and beliefs, and the relationship between beliefs and actual states of affairs. If these assumptions prove to be false, then doubts can be cast over the conclusions made in both parts of the research.

A limitation in the empirical work was the fact that the subject had a knowledge of logical deduction. It is possible that this prior understanding enabled a better enunciation of the logic in thinking (as presented in the verbalisations) than may have been otherwise present. Secondly, there was only one subject. I was able to detect similar patterns of reasoning across different verbalisations, so the data is at least reliable. However, drawing general conclusions is problematic. It is not possible to generalise the findings to other thinkers without making many assumptions about the similarity of thinking across humans. Lastly, while the verbalisations may have represented some of the thinking that occurred, it is possible that they did not represent all the thinking.

8. Conclusion

Logical deduction as a *thinking* process is more accurately called deductive-like inferring. It is a process that resembles ‘traditional’ logical deduction in form but does not have the same guarantee of truth or correctness. It is, however, a process that can be applied usefully to thinking in high school physics, particularly in tests and examinations.

Given that the conclusions drawn using deductive-like inferring are, ultimately, unpredictable, there are limits to the improvement that can be made to it. Nevertheless, a greater engagement of teachers and students with metacognition and thinking skills, including the specific teaching of logic, is likely to be of great assistance. To clarify this matter further, more research into the role and improvement of logical deduction is warranted.

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Appendix

Truth Table Example

Consider the disjunctive syllogism:

A or B

Not A

Therefore, B

An instantiation of this syllogism is:

I always leave my keys on the bench or on the hook

They are not on the bench

Therefore, they must be on the hook

To determine validity, a truth table (Table 1) can be constructed. All possible combinations for the truth and falsity of propositions A and B are considered and then, for each combination, the premises and conclusions are assessed as true or false. For instance, ‘A or B’ is ‘true’ when A is true, B is true or both A and B are true. ‘A or B’ is false when both A and B are false.

Table 1

			Premise 1	**Premise 2**	**Conclusion**
	A	**B**	**A or B**	**Not A**	**B**
1.	F	F	F	T	F
2.	F	T	T	T	T
3.	T	F	T	F	F
4.	T	T	T	F	T

We see that this is not a tautology, as there are cases where the conclusion is false. It is deductively valid because, when all the premises are true, the conclusion is also true (as shown in row 2).