Should problem solving precede explicit instruction when element interactivity is high?

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Should problem solving precede explicit instruction when element interactivity is high?

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My literature review is partially comprised of an intervention study titled "Problem-solving or Explicit Instruction: Which Should Go First When Element Interactivity Is High?" published in 2020 in the journal, Educational Psychology Review, alongside my co-authors, Slava Kalyuga and John Sweller. All of Section 3.3, the first two paragraphs of section 3.4 and the 2nd, 3rd, 4th and 6th paragraphs of section 3.5 of the thesis are taken directly from this paper and this is acknowledged in a footnote. I contributed greater than 50% to the writing of this paper and these passages are reproduced with permission of the co-authors. I have acknowledged the work of my co-authors - who are also my supervisors - in the acknowledgements section.

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Abstract

The concept of Productive Failure posits that a problem-solving phase prior to explicit instruction is more effective than explicit instruction followed by problem solving. However, Cognitive Load Theory makes the opposite prediction that explicit instruction followed by problem solving is more effective than a problem-solving phase prior to explicit instruction when element interactivity is relatively high. The literature for both Cognitive Load Theory and Productive Failure are reviewed and the concept of element interactivity is defined and described. The competing predictions of Productive Failure and Cognitive Load Theory are tested via a series of five, fully randomised, controlled experiments conducted with learners in Years 5 and 6 (approximately 10-12 years of age) of an independent Australian school learning the physics concept of energy efficiency. The first three experiments did not provide strong evidence for the superiority of either order due to a series of factors unrelated to the hypotheses. Following refinement, including the introduction of a novel experimental procedure designed to eliminate a key confound, Experiments 4 and 5 provide strong evidence that explicit instruction prior to problem solving is the superior sequence in this context. In Experiment 4, where element interactivity was high ($N = 71$), explicit instruction followed by problem solving was found to be superior to the reverse order for performance on problems similar to those used during instruction as well as transfer problems. In Experiment 5 ($N = 64$), where element interactivity was reduced compared to Experiment 4 but still relatively high, explicit instruction followed by problem solving was found to be superior to the reverse order for similar problems, with no difference on transfer problems. The contradictory predictions and results of a productive failure approach and cognitive load theory are discussed using the concept of element interactivity. Specifically, for learning where element interactivity is high, explicit instruction should precede problem solving.

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I also wish to thank Wendy Xiao of ReadWorks, the source of the reading 'filler' task that is used in Experiments 2-5, for giving permission to reprint this task in the appendices along with the other experimental materials.

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Introduction

Determining the most effective instructional approaches is a key aim of educational psychology with wider societal implications. One factor that has dominated the discussion is the degree of explicit instructional guidance that learners should be provided with and when this should occur (see e.g. Tobias & Duffy, 2009). On the one hand, there are those who argue that learners should discover all or some of the targeted knowledge and skills for themselves (e.g. Bruner, 1961; Papert, 1980; Hmelo-Silver, Duncan, & Chinn, 2007). This is often referred to as a 'constructivist' approach, although this term is disputed and regarded by some as denoting a theory of learning and not an instructional approach (Bransford, Brown, & Cocking, 2000; Mayer, 2004; Hattie, 2008). On the other hand, there are those who argue that explicit instruction, where full instructional guidance is provided to learners when new concepts are first introduced, is more effective (Kirschner, Sweller, & Clark, 2006; Rowe, 2006; Rosenshine, 2009; Zhang, Kirschner, Cobern, & Sweller, 2021).

In recent years, perhaps signalling that the case for providing instructional guidance is strong, a significant group of researchers have moved on to empirically investigate and debate the *sequence* of instructional events. Assuming that full instructional guidance should be provided at some point in an instructional episode, the question arises as to whether this guidance should be provided from the outset, or after a period when learners first wrestle with relevant problems, questions or tasks for themselves. The sequence of problem solving followed by explicit instruction has become known by several names such as 'Inventing to Prepare for Learning' (Schwartz & Martin, 2004). However, the name under which this sequence has been most extensively researched in recent years is 'Productive Failure' (Kapur, 2008). As Productive Failure, this concept has entered the wider public discussion about education (e.g. Spinney, 2021).

However, the evidence to support Productive Failure is not conclusive. While there is strong evidence to support the effectiveness of learners generating answers for themselves, this tends to come from contexts such as learning lists of word pairs (Slamecka & Graf, 1978; Hirschman & Bjork, 1988; Schwarz, Lindgren, & Lewis, 2009). Such learning objectives may not be representative of typical educational learning objectives and are low in 'element interactivity' because each item in the list can be learnt in isolation from each other item. In contrast, learning to solve problems such as '$3x = 18$, solve for x' is high in element interactivity for novice learners because they consist of multiple elements (such as '3', 'x', '=' and '18') and each element of the problem has a relationship with each other element (Chen, Kalyuga, & Sweller, 2017). Productive Failure is often proposed for learning educationally relevant concepts that, for novices, are relatively high in element interactivity, such as computing standard deviation (see e.g. Kapur, 2014). There is a body of empirical evidence to support this approach. However, there is also a body of conflicting empirical evidence that appears to demonstrate that Productive Failure is less effective than the alternative instructional sequence of explicit instruction followed by problem solving. This latter finding is consistent with the predictions of the theoretical framework of Cognitive Load Theory. These bodies of evidence will be discussed in Chapter 3.

Cognitive Load Theory (Sweller, Ayres, & Kalyuga, 2011) provides a theoretical perspective that challenges the effectiveness of Productive Failure when element interactivity is high. Cognitive Load Theory assumes that new academic concepts must pass through a highly constrained working memory before being stored in long-term memory and therefore the problem-solving phase of Productive Failure would overload working memory. Cognitive Load Theory and Productive Failure therefore make competing predictions that can be tested empirically.

The purpose of the empirical research described in Chapters 4 and 5 is to investigate the Productive Failure sequence in the context of calculating energy efficiency. This context was selected because of the wider societal benefits of young people having a better understanding of energy efficiency in an era of climate change. It is also a concept that is high in element interactivity for novice learners and is therefore challenging for young people to learn.

This thesis therefore consists of three parts. Chapters 1 – 3 are a literature review of human cognitive architecture and its implications as formulated in the framework of Cognitive Load Theory, followed by a review of the evidence surrounding Productive Failure. Chapters 4 and 5 introduce and describe a series of five empirical studies that test the competing predictions of Cognitive Load Theory and Productive Failure in the context of learning to calculate energy efficiency. Chapter 6 is a general discussion, including conclusions and limitations.

Chapter 1
Human Cognitive Architecture

The design of instructional procedures should take into account human cognitive architecture. Cognitive Load Theory posits that knowledge we have not evolved to acquire – biologically secondary knowledge – must first be processed in a constrained working memory before passing into long-term memory where it is held in the form of schemas. Instructional procedures therefore need to accommodate the constraints of working memory.

1.1 Categories of knowledge

This chapter will make use of a taxonomy of knowledge types drawn from David C. Geary's evolutionary educational psychology (Geary 2007, 2008; Geary & Berch, 2016). Geary makes a distinction between biologically primary knowledge and biologically secondary knowledge and this has relevance to the design of instructional procedures.

Biologically primary knowledge is characterised by the fact that humans acquire it with little formal instruction across all world cultures. Biologically secondary knowledge is created by specific cultures rather than being present in all cultures and requires formal instruction and effort in order to acquire.

1.1.1 Biologically primary knowledge

Biologically primary knowledge has been proposed as a category of knowledge that we have evolved to acquire (Geary, 1995). For instance, virtually all children learn to speak their native language and yet they are not born with this knowledge, nor have they been explicitly instructed in how to move their lips, tongues and mouths and modulate their breathing in order to make the sounds used by this language. Instead, they have acquired this knowledge from their environment.

Other examples of biologically primary knowledge include knowledge of what food can be eaten and where it can be found that may be described as ‘folk biology’, as well as ‘folk psychology’, an understanding of others that is necessary for human cooperation and competition. Biologically primary knowledge is characterised by the fact that it is present in all human cultures and is easily and subconsciously acquired without needing to be explicitly taught. It arises from particular constraints such as those imposed by the human skeleton combined with a bias to engage in certain activities. Together, these allow biologically primary knowledge to be adapted to local conditions.

1.1.2 Biologically secondary knowledge

Biologically secondary knowledge has been proposed as a category of culturally specific knowledge that we have not evolved to acquire (Geary, 1995). Writing has only come into existence relatively recently in human history. The development of cuneiform writing in ancient Sumer dates to roughly 5000 years ago (Postgate, 1992), the history of written Chinese extends back to the second century BCE (Norman, 1988) and the Zapotec writing of ancient Mesoamerica can be dated to approximately 500 BCE (Marcus, 1980). Mass literacy is an even more recent development, with mass literacy in Europe only achieved within the last few hundred years (Vincent, 2000). By contrast, human evolution works on a longer timescale, with modern humans diverging from Neanderthals and Denisovans a few hundred thousand years ago and modern humans in Europe and Asia diverging tens of thousands of years ago (Scally & Durbin, 2012).

There therefore does not appear to have been sufficient time for mechanisms for acquiring the ability to read and write to be affected by evolution. Moreover, in contrast to oral language, writing is not universal among the cultures of the world (Cram & Neis, 2018). It would therefore be wasteful and inefficient for the evolutionary process to develop the ability to acquire writing and yet for this ability to lie dormant for most of human history and prehistory and in many humans alive today.

Biologically secondary knowledge builds upon, and extends, biologically primary knowledge. According to the simple view of reading (Gough & Tunmer, 1986), an empirically validated, simplified model of the reading process, (Hoover & Tunmer, 2018; Hjetland, Lervåg, Lyster, Hagtvet, Hulme, & Melby-Lervåg, 2019), reading comprehension is the product of two factors: word decoding and language comprehension. Word decoding is the process of converting written symbols into words and language comprehension is the process of retrieving literal and implied meaning from these words when used in speech. Word decoding can be thought of as a biologically secondary process because it is only present in cultures that have developed written language, albeit a process that co-opts the more fundamental, biologically primary process of segmenting language sounds or 'phonological processing' (Geary, 1995). The words are then processed according to the biologically primary mechanisms that have been developed for processing spoken words in the grammar of that specific language. The meaning of those words may then draw upon further biologically primary or secondary knowledge, depending upon the subject matter and vocabulary (Lespiau & Tricot, 2019). A text about a family quarrel, for example, may draw largely upon biologically primary, evolutionarily salient, knowledge, whereas a text describing an efficient manufacturing process may draw largely upon biologically secondary knowledge.

Given that humans do not possess evolved systems for acquiring biologically secondary knowledge, we may predict that the acquisition of such knowledge will be more effortful than the acquisition of biologically primary knowledge. This is borne out by the commonplace observation that children acquire oral language more easily than the ability to read and write and, more specifically, the finding that teaching strategies involving immersion in printed material are less effective than those that involve more explicit teaching of letter-sound relationships (Ehri, Nunes, Stahl, & Willows, 2001). Moreover, in an environment plentiful in potential sources of biologically secondary knowledge, humans would benefit from a mechanism for selecting appropriate knowledge in order to avoid the rapid and potentially damaging accumulation of large amounts of information of varying quality and utility.

1.1.3 Summary

Cognitive Load Theory draws upon the distinction Geary makes between biologically primary and biologically secondary knowledge. Biologically primary knowledge is knowledge we have evolved to acquire and is the product of more recent cultural innovation. We therefore have not evolved to acquire this knowledge and this may explain why strategies such as immersion are not as successful for obtaining biologically secondary knowledge as they are for obtaining biologically primary knowledge. Given the large amount of biologically secondary knowledge that is potentially acquirable from the environment, human cognition requires a system for processing this knowledge. In the next section, human cognition will be described as a natural information processing system.

1.2 Information processing in evolution and cognition

Cognitive Load Theory (Sweller, Ayres, & Kalyuga, 2011) posits that the human mind, when dealing with biologically secondary knowledge, may be modelled as a natural information processing system. As such, it is analogous to biological evolution which is another natural information processing system in which an organism's genome acts as the information store.

Natural information processing systems have two ways of acquiring new information. The first method is a random-generate-and-test approach that is described in Cognitive Load Theory as the 'randomness as genesis' principle (Sweller & Sweller, 2006). In biological evolution, a mutation may occur randomly to a gene within an organism's genome. This may have no effect or may confer a disadvantage on the organism carrying this mutation. A disadvantage will reduce the organism's capacity to pass this mutation on to subsequent generations. However, the mutation may alternatively confer an advantage on the organism, increasing the likelihood of it being passed to subsequent generations (see e.g. Dobszhansky, 1937; Dawkins, 1976). In this manner, each mutation is tested for effectiveness with adaptive mutations retained and non-adaptive ones discarded. Any mutation that confers an advantage therefore adds to the sum of information stored in the species' genome. A direct analogy between the accumulation of information via the process of biological evolution and the accumulation of knowledge has been drawn by a number of authors (e.g. Popper, 1972; Dawkins, 1976; Siegler, 1996).

The second method by which information may be acquired by an organism's genome uses the 'borrowing and reorganising' principle. Information from one genome is borrowed and reorganised into another genome. In the case of biological evolution, this process can take place through sexual reproduction or direct transfer of genes between bacteria, both of which will change the information stored in the genome (see e.g. Michod, Bernstein, & Nedelcu, 2008). In contrast, most asexual reproduction, such as parthenogenesis, results in a copy of the original genome, although recombination of the genome may occur, depending on the mode of asexual reproduction (Mittwoch, 1978).

In biological evolution, the genome therefore acts as a store of information that can potentially be altered over time. In human cognition, long-term memory, to be described more fully below, acts as an analogous store of information. The information in long-term memory can be altered by means analogous to those that alter the information stored in the genome. Information stored in long-term memory may be created through a random-generate-and-test procedure (the 'randomness as genesis' principle) or it may be borrowed and reorganised from the long-term memories of other individuals (the 'borrowing and reorganising principle'). Given that the genome and long-term memory are both natural phenomena, we can describe both as natural information stores and the processes of acquiring and changing the information available in these stores as natural information processing systems.

1.2.1 Summary

Human cognition can be modelled as a natural information processing system. An analogy can be made between human cognition and biological evolution. Both human cognition and biological evolution share features such as the 'random generate and test' and 'borrowing and reorganising' principles for acquiring new information. Both systems need an information store. In human cognition, this is long-term memory which will be examined in the next section.

1.3 Long-term memory

Long-term memory is the information store used by human cognition, and a natural information processing system. It is connected to learning, which can be defined as a change in long-term memory (Kirschner, Sweller, & Clark, 2006).

Information can be accrued in long-term memory either through the process of borrowing and reorganising or by random-generate-and-test. Unlike biologically primary knowledge, biologically secondary knowledge must first pass through working memory into long-term memory. There are no obvious limits on the capacity of long-term memory or on the duration of time over which information may be stored in long-term memory (Brady, Konkle, Alvarez & Olivia, 2008; Sweller, Ayres, & Kalyuga, 2011).

1.3.1 Schemas

Information is stored in long-term memory in the form of schemas. A schema can be defined as a, "cognitive construct that permits us to classify multiple elements of information into a single element according to the manner in which the multiple elements are used" (Sweller, Ayres, & Kalyuga, 2011).

The concept of schemas can be traced back to *Plato* and his conception of ideal types (Russell, 2001). A perfect circle may not exist in nature, perhaps, but humans possess a concept of a perfect circle to which observable circles may be assimilated. Rather than storing information in a set of mental filing cabinets according to when that information was acquired, the mind appears to link information into networks based upon semantic relationships. For instance, when presented with a sequence of randomly arranged items, test participants tend to recall them in clusters that belong to the same category (Bousfield, 1953).

Schemas are generally considered to be acquired through learning, although some basic schemas may be innate. Schemas may exist for everything from classes of objects to abstract concepts, and schemas may subsume other schemas i.e. a component of one schema may itself be a schema (Seel, 2012).

It is worth contemplating that a perspective on schema development in long-term memory that draws upon the analogy of biological evolution would appear to privilege schemas that are of utility to the individual who possesses them. Given that one function of education is for learners to gain schemas that accurately represent what is known about the world, this introduces an interesting tension. From an evolutionary perspective, a schema that is a false representation of the world but that confers an advantage on the individual who possesses it – e.g. by conferring status within an in-group – would be privileged over a schema that is a more accurate representation of the world but that does not confer this advantage. This could account for a number of cognitive biases (Haselton, Nettle, & Andrews, 2005). Alongside the 'narrow limits of change' principle, which will be discussed below, we may predict that these conservative tendencies would work against the assimilation of technical schemas consisting of biologically secondary knowledge that, although more accurately reflecting what is known about the world, do not confer any obvious or immediate advantage to the individual who possesses them. This would therefore represent a key problem for instructional designers.

1.3.1.1 Schema automation

Sweller, Van Merriënboer and Paas (1998) suggested that schemas may exist in long-term memory in varying degrees of automation. Automation reduces the working memory load by reducing the number of elements that must be consciously processed in working memory. Sweller, Van Merriënboer and Paas give the example of reading and the fact that most adults are able to read text without consciously processing each of the letters in each word.

To give another illustrative example of an automated schema, consider an individual who possesses a schema for basic algebra. They may view the equation $3x = 18$ and almost instantaneously conclude that x has a value of six. Yet this would not be obvious to someone who lacked this schema. To come to the correct conclusion, you need to know a number of key concepts. First, you need to know that letters commonly represent unknown numbers and so the letter, x, in this equation represents a number. You need to know that $3x$ is a way of representing $3 \times x$ or 'three lots of x'. You need to understand the principle of equivalence i.e. that the '=' sign does not mean, as many children often think, a command to write an answer (see e.g. Rittle-Johnson, Matthews., Taylor & McEldoon, 2011), it means that what is on the left hand side of the sign is of the same value as what is on the right hand side of the sign. You need to know that if 3 lots of x are equal to 18 then x must equal 18 divided by three i.e.

you need to understand that multiplication and division are inverse processes. Finally, in order to almost instantaneously conclude that x is six, you need to be able to quickly retrieve the maths fact that $3 \times 6 = 18$ and so $18 \div 3 = 6$.

This example illustrates how schemas bring together interrelated elements of information into a coherent whole and is consistent with experimental findings. For instance, Chi, Feltovich and Glazer (1981) presented physics novices and experts with sets of physics problems to categorise. The novices tended to categorise the problems according to their surface features, such as whether they involved an inclined plane. The experts tended to categorise the problems based upon the solution methods required to solve them. This indicates that the experts possessed schemas for each solution method that connected the different elements in that method into a categorisable whole which they could then map onto the problems they were presented with.

Cognitive Load Theory proposes that schemas can be brought into working memory with little effort, as in the algebra example above, and treated as individual elements, circumventing some of the capacity limitations of working memory. Biologically primary knowledge can pass directly into long-term memory, but biologically secondary knowledge must first be processed in working memory (Sweller, Ayres, & Kalyuga, 2011).

1.3.1.2 Schema acquisition

Jean Piaget (1936) suggested that new knowledge may be either *assimilated* or *accommodated* by existing schemas. If an individual already possesses a suitable schema, then they may simply slot the new information into that schema. Perhaps, for example, an individual who is familiar with dogs encounters a new breed of dog. The new breed may be assimilated to the existing schema the individual possesses for dogs. However, sometimes new information cannot be easily added to an existing schema and, in this case, it may be necessary to transform the schema such that the new information can be accommodated. For instance, an individual may possess a schema for mammals that includes the concept that mammals are viviparous i.e. they give birth to live young rather than lay eggs. However, when this individual learns new information about monotremes, a class of mammal that lays eggs, they will need to adapt their mammal schema accordingly.

The relative ease of assimilation suggests that individuals may be biased towards gaining knowledge that can be assimilated rather than accommodated. This is borne out by experimental evidence such as that obtained by Bartlett (1932). In this experiment, participants were given a story to read called *The War of the Ghosts*. This was a translation of a North American folk tale that was culturally unfamiliar to the participants. Participants were then required to recall the tale at varying time intervals. Bartlett observed that some features were retained and others lost, as we might expect. However, other features were changed. Some of the terminology became more journalistic and contemporary than in the original version. In the original story, the characters had set out to hunt seals but this became a fishing trip in some recalled versions. Participants had apparent difficulty with two features of the story: the ghosts and the death of a character. They dealt with these difficulties either by omitting them or rationalising them. In one version, for instance, 'Ghosts' became the proper name of a clan.

This demonstrates that long-term memory does not record new information verbatim and store it in a filing system similar to those used by computers. Rather, new information becomes assimilated or accommodated to existing schemas.

1.3.1.3 Schema maintenance

One commonplace observation that is perhaps discouraging for educators is that we forget much of what we learn in school. One possible explanation for this effect is that schemas are lost over time, perhaps through disuse. This would be less of a problem if, in the process of acquiring schemas, we developed general purpose reasoning or problem-solving skills. However, the available evidence suggests that such skills, insofar as they do exist and are general-purpose, are biologically primary and so the acquisition of biologically secondary schemas should do nothing to improve them (Tricot & Sweller, 2014).

In sum, this appears to provide a case against formal education. Yet it may be worth re-examining the original assumption of a binary between existing and lost schemas. It may in fact be more accurate to postulate an intermediate stage where schemas are somewhat latent. Bjork and Bjork (1992) proposed a 'new theory of disuse' in which items in long-term memory have both a storage strength and a retrieval strength. Retrieval strength may be boosted by the act of retrieval itself i.e. retrieving an item facilitates its future retrieval. There is ample evidence that retrieval enhances learning, at least under certain circumstances (see e.g. Karpicke, 2012) and this may be a possible mechanism. This theory allows for latent schema states that are relatively high in storage strength but relatively weak in retrieval strength.

The utility of a latent, less salient, schema may also depend upon *how* we seek to use it. For instance, writing requires us to generate words and phrases and so the associated schemas for these words and phrases must be high in retrieval strength. In contrast, reading requires us only to recognise words and phrases supplied by the text. This gives us additional cuing information and so may require only an intermediate retrieval strength. There is a wealth of experimental evidence to suggest that recognising correct answers e.g. in multiple choice tests is easier than recalling them (e.g. Bahrick, 1984; Conway, Cohen & Stanhope, 1991). Differences in retrieval strength may therefore account for a common observation such as, "I cannot think of Jack's surname, but I'll recognise it when you say it."

1.3.2 Summary

Learning is a change in long-term memory. Knowledge is organised in long-term memory in the form of schemas. Schemas are networks of interconnected information organised through semantic relationships that can be brought into working memory with little effort. Schemas can change via assimilation, by adding new knowledge to a pre-existing schema, or accommodation, by deforming existing schema to take account of new knowledge that is inconsistent with current schemas. An evolutionary perspective suggests schemas will be selected for their utility rather than the accuracy with which they represent the world and this suggests a problem for instructional designers. Schemas that are disused may not be lost and may be retrievable through the right cues. Biologically secondary knowledge must pass through working memory into long-term memory and so working memory is examined next.

1.4 Working memory

Working memory embodies the 'narrow limits of change' principle of natural information processing systems. There is an abundance of biologically secondary knowledge that could potentially be subsumed into the long-term memories of humans. This may be available through the borrowing and reorganising principle and may range from the structure and function of a magnetometer to the contents of *Hello* magazine. Alternatively, it may be available through random-generate-and-test procedures.

It is clear that all such available knowledge is not of the same value to an individual. Some knowledge may be redundant. Other knowledge may be simply false or the product of one person's attempt to mislead another. Equally, unlike biologically primary knowledge, we have not evolved mechanisms to direct us as to which of this knowledge is salient and valuable. The assimilation of biologically secondary knowledge could therefore potentially lead to chaotic and possibly harmful changes to long-term memory.

We have no template for organising knowledge produced through random-generate-and-test and this gives further insight into the issue. For three new elements of knowledge, we can deduce from the mathematics of permutations that there are 3! or six ways of arranging these elements. For ten elements, this balloons to 10! or 3,628,800. It is likely that biologically secondary knowledge often involves elements that are borrowed and reorganised and elements that are randomly generated. For instance, we may obtain information from another individual but without information on how to organise this into a relevant schema. The possibilities for such organisation are therefore vast.

The narrow limits of change principle restricts the number of new elements that may be processed at any time. This in turn restricts the number of possible relationships between these elements. This is analogous to the way in which the epigenetic system restricts the scope for change in an organism's genome in biological evolution (Sweller & Sweller, 2006).

It has been established for some time that there are constraints imposed by human cognitive architecture on the processing of new information. In 1956, George Miller presented evidence from a range of empirical sources that demonstrated such limitations (Miller, 1956). For instance, in absolute judgement experiments, participants would be presented with a number of different stimuli that vary by one factor only. As the number of stimuli increased, a point was reached when the participants could no longer discriminate between the different stimuli and began to make errors. Miller noted that this 'channel capacity' was around seven items. A similar number was generated on tests of what Miller termed 'immediate memory'. Whereas the previous stimuli were presented at different points in space, these stimuli occurred sequentially in time. Participants were presented with different numbers of stimuli and then asked to recall them. Again, the limit for successful recall was around seven items.

Subsequently, Atkinson and Shriffin (1968) proposed a model of human cognitive architecture that included a ‘short-term store’ and a ‘long-term store’. In line with Miller’s observations, the number of items that can be maintained in short-term memory has a limit of five to nine items, with large sequences drawing upon the long-term store to supplement the capacity of the short-term store.

‘Working memory’ has been suggested as an alternative name for the short-term-store (Atkinson & Shriffin, 1968). In 1974, Baddeley and Hitch drew upon experimental evidence to present a detailed model of working memory (Baddeley & Hitch, 1974). As the name implies, working memory is not modelled as a static information store – it is capable of processing elements of information. This model has continued to develop such that it is now conceived as consisting of a central executive that coordinates a number of subsidiary systems, the two most important of which are an ‘articulatory loop’ – also known as the ‘phonological loop’ (Baddeley, Gathercole & Papagno, 1998) – and a ‘visuo-spatial scratchpad’ (Baddeley, 1992). See Figure 1.1.

Baddeley (1992) expressed doubts about the need for a coordinating central executive and Sweller, Ayres, & Kalyuga (2011) have suggested that proposing such an executive requires us to ask what controls the executive and therefore implies an infinite regress of central executives. Instead, resource deployment in working memory may be coordinated by schemas held in long-term memory. This is congruent with the suggestion that an entire schema may be manipulated in working memory as a single element and therefore can bypass the constraints of working memory.

The lack of a central executive is an additional parallel between information processing in human cognitive architecture and information processing in evolution by natural selection. Neither process is coordinated centrally. In contrast, computers have a central executive in the form of a central processing unit. The lack of a central executive therefore implies that evolution is a superior analogy for human cognition than the information processing performed by a computer.

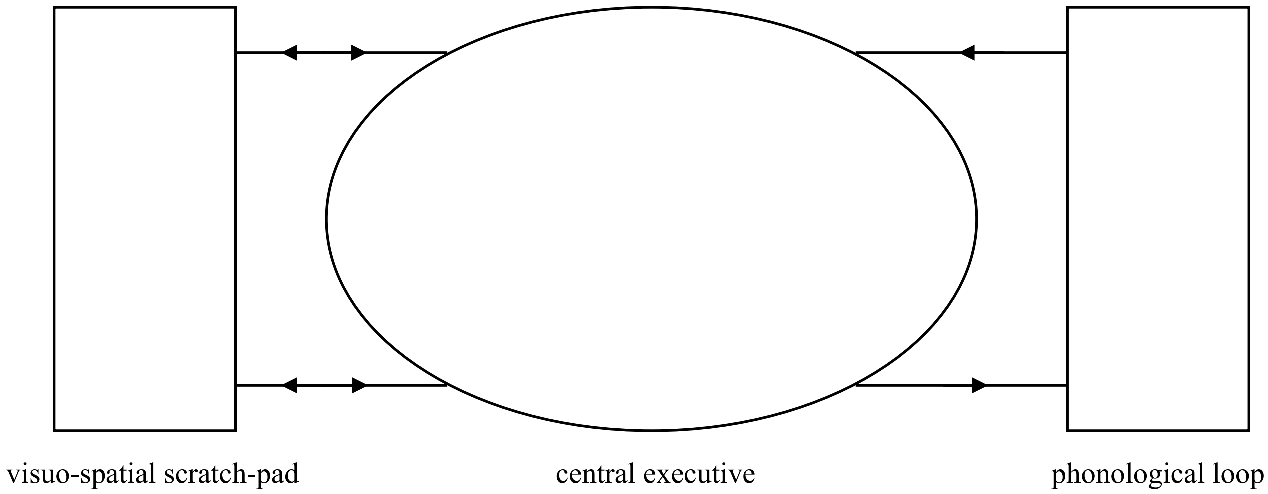

Figure 1.1. A simplified model of working memory that includes a central executive (after Baddley, 1992)

Current estimates of the capacity of working memory set the limit at about four elements to process at any given time, reflecting the processing load implicit in working memory (Cowan, 2001).

Instructional procedures must take account of the capacity of working memory. If learners are presented with too many elements to process at once, then working memory may become overloaded, leading to little learning. It is also possible for working memory capacity to be deployed in successfully solving a problem but with no learning taking place about overall solution patterns (Sweller, Mawer & Howe, 1982). This may be because there is no capacity left in working memory to pay attention to these patterns.

In contrast, given that some problems may be solved entirely within one schema drawn from long-term memory, such as in the algebra example above, it is possible that some learning tasks that are simple or, equivalently, that learners are highly familiar with, may fail to sufficiently engage working memory and therefore fail to lead to the changes in long-term memory that are identified with learning.

1.4.1 Summary

Evidence suggests that working memory is severely constrained, with the capacity to process around only four items at a time. This embodies the ‘narrow limits of change’ principle and acts to prevent the chaotic acquisition of large amounts of low-utility, biologically secondary knowledge. Although a central executive is proposed in some models of working memory in order to coordinate the action of working memory, this presents a problem of what controls the central executive and a superior model may be one that views working memory as being controlled by schemas in long-term memory.

1.5 The Environmental Organising and Linking Principle

From the above discussion, we have seen that long-term memory is effectively limitless and that working memory is severely constrained. Moreover, entire schemas stored in long-term memory may be processed with little effort in working memory in stark contrast to new information. These features of human cognitive architecture are embodied in the ‘environmental organising and linking principle’ (Sweller, Ayres, & Kalyuga, 2011). Whereas new information is unstructured and therefore potentially combined in a large number of ways – mathematically, this is known as a ‘combinatorial explosion’ – information stored in long-term memory is highly structured. Human cognitive architecture therefore constrains new information in working memory in order to prevent this combinatorial explosion and yet there is no need to do the same with the organised information stored in long-term memory. Consequently, when information stored in long-term memory is brought into working memory, it operates under no known constraints. The role of working memory is to mediate environmental signals so as to direct which schemas to activate.

The environmental organising and linking principle is analogous to the way in which the epigenetic system marshals gene expression in evolution, an analogous natural information processing system. In evolution there are limits to the amount of new information in the form of mutations that the epigenetic system can deal with but there are no effective limits on the amount of previously organised genetic information that can be processed.

1.6 Summary of Chapter 1

Cognitive Load Theory assumes a distinction between biologically primary knowledge and biologically secondary knowledge. Biologically primary knowledge, such as where to find food or how to speak the language of the community a child is born in to, is knowledge that we have evolved to acquire and this knowledge passes directly into long-term memory. Biologically secondary knowledge is the product of human culture and is not universally acquired across different cultures. Such knowledge includes reading, writing and mathematics. Humans have not have sufficient time to evolve mechanisms for acquiring this knowledge.

Human cognitive architecture is an information processing system analogous to biological evolution. Long-term memory operates as an information store similar to the biological genome. New, biologically secondary information may be acquired by a random generate-and-test procedure analogous to genetic mutation, or by borrowing and reorganising information from another individual, analogous to sexual reproduction or the direct transfer of genetic information between bacteria. To avoid rapid and potentially catastrophic change to the information store, new, biologically secondary information must pass through a limited working memory that embodies the narrow limits of change principle analogous to the epigenetic system in evolution.

Knowledge is held in long-term memory in the form of webs of interconnected concepts known as ‘schemas’. Once formed, schemas can be activated with relatively little effort and be brought to bear upon new information or problems. Schemas are dynamic and new knowledge is assimilated or accommodated to existing schemas. Schemas can exist with different levels of saliency or latency and usage of a schema through active retrieval can boost the retrieval strength of items within the schema.

The quite different properties of working and long-term memory result from the nature and organisation of the information being processed as embodied in the environmental organising and linking principle.

Working memory consists of separate components for processing auditory and visual information. The most common model of working memory – posited by Baddeley – also consists of a central executive to coordinate activity. However, this implies an infinite regress of central executives and so Cognitive Load Theory posits that coordination is controlled by schemas in long-term memory. The limits of working memory are a key constraint on instructional designers.

Chapter 2
Cognitive Load Theory

Cognitive Load Theory views human cognitive architecture as a natural information processing system. Cognitive Load Theory seeks to explain the cause-and-effect relationship between the information processing load – 'cognitive load' – induced in working memory due to different instructional materials and procedures and the construction of knowledge in long-term memory. The purpose of the theory is to generate novel instructional designs.

Cognitive Load Theory applies to biologically secondary knowledge that is subject to working memory constraints as outlined in Chapter 1. The constrained nature of working memory implies two main considerations when designing instructional procedures. Firstly, sources of extraneous cognitive load that are unnecessary, such as distractions introduced by instructional materials or instructional methods, should be minimised. Secondly, sources of load that are relevant to the concepts to be learnt, such as the intrinsic complexity of a task, should be optimised but held within the limits of working memory. This leads to a number of 'effects' where certain instructional procedures that minimise extraneous load and optimise intrinsic load, while containing it within the limits of working memory, are shown to have a greater effect on learning than alternatives procedures. Moreover, this process is dynamic. As learners construct schemas in long-term memory, they are able to bring these entire schemas to bear on complex problem situations without imposing an excessive load on working memory and so a task that would consume the working memory of a novice would be easily completed by a relative expert. Therefore, the optimal complexity of learning materials will increase as learners become more expert.

2.1 Definitions of explicit teaching and problem solving

In the investigations described in the empirical studies in Chapters 4 and 5, a distinction is made between explicit instruction and problem-solving instructional phases. It is therefore necessary to clearly define such phases.

Unfortunately, such definitions are problematic. A term that could perhaps be used instead of explicit teaching is ‘direct instruction’. However, Barak Rosenshine has identified at least five different ways that this term is used (Rosenshine, 2008). These include pejorative senses. Some of these definitions take the correlational teacher effectiveness research of the 1950s-1970s as their origin (Rosenshine, 2012). Commenting on the same body of evidence, Brophy and Good (1984) described the process of ‘active teaching’, a form of instruction “in which the teacher presents information and develops concepts through lecture and demonstration, elaborates this information in the feedback given following responses to recitation or discussion questions, prepares the students for follow up seatwork activities by giving instructions and going through practice examples.” (p. 111).

However, the terms used by Rosenshine, Brophy and Good in this way clearly refer to an ongoing process rather than a single instructional phase. What they have in common is that new concepts are fully explained and new procedures are fully demonstrated prior to learners being asked to engage with these concepts and processes.

Therefore, in the following discussion, ‘explicit instruction’ will refer to an instructional phase where new concepts and procedures are fully explained and demonstrated.

Problem solving has a long pedigree as a pedagogical tool, not least through the work of Jerome Bruner on discovery learning (1961). However, for the following discussion, it will suffice to define problem solving as learners attempting to answer questions for which relevant concepts and solution procedures have *not* been fully explained to the learners in advance. Thus, the key difference between explicit instruction and problem solving is that concepts and procedures are fully explained in the former, prior to learners being asked to use them to solve problems whereas in the latter, some of the relevant concepts and procedures are *not* fully explained prior to the learners being asked to solve problems that rely on these concepts and procedures.

2.2 Development of Cognitive Load Theory

The fact that what we now term 'working memory' has a limited capacity has been known since at least George Miller's 1956 paper in which he referred to the span of what he termed 'immediate memory'. However, Miller's argument was in the context of experiments such as recalling a sequence of stimuli. The implications of such a limit to theories of instruction were not immediately obvious.

In contrast, De Groot's 1940s work on chess expertise (De Groot, 1978) should have perhaps made clear to educational researchers the instructional implications of long-term memory. De Groot established that the difference in skill between Candidate Masters (very good players) and Grand Masters (the best players) was not a function of superior search patterns, a finding that was perhaps contrary to contemporary expectations. These findings were then corroborated and extended by de Groot's student, Rickent Jongman (De Groot, Gobet, & Jongman, 1996). Through this body of work, the central contribution of *experience* to expert performance through its impact on long-term memory became clear. However, as Sweller, Van Merriënboer and Paas (2019) argued, the instructional implications of the role of long-term memory were initially ignored and this may be because long-term memory has been associated with rote learning.

Cognitive Load Theory began development in the 1980s (Sweller, 2016). One early experiment that set the foundations for Cognitive Load Theory is relevant to this discussion

(Sweller, Mawer and Howe, 1982). Undergraduate students were required to transform a given number into a goal number using a sequence of moves. However, only two moves were allowed: multiply by 3 or subtract 29. Each problem had a unique solution. However, the researchers had designed these problems so that each one was solved by an alternating sequence of moves such as $\times 3, -29, \times 3, -29$ or $\times 3, -29, \times 3, -29, \times 3, -29$. While the undergraduate students were successful at solving the problems, few noticed the pattern of alternating moves. This may be because the problem-solving activity consumed all available working memory capacity so that there was none remaining to notice a pattern. As we will see in the next chapter, proponents of the theory of Productive Failure posit that problem-solving search can prime learners for later explicit teaching and so this early finding in the field of Cognitive Load Theory is relevant to this proposition.

Such a finding also has profound implications for classroom teaching. It is counterintuitive that learners may successfully complete a task and yet not learn from the process. If teachers are using successful task completion as a proxy for learning then they may be being misled.

During the 1980s, two key experimental findings established the field of Cognitive Load Theory. The first was the finding that learning was enhanced in a particular class of problems if learners were not set a specific goal. This is known as the 'goal free effect' to be described more fully below and it can be understood in terms of removing the cognitive load associated with monitoring progress towards the goal. The second was the finding that studying worked examples was more effective for novice learners than solving equivalent problems. This is the 'worked example effect' to be described more fully below. The worked example effect cast doubt on the proposition, influential in the field of educational psychology at least since the work of Bruner in the 1960s (see e.g. Bruner, 1961), that discovery learning was an effective and desirable teaching method.

As more experimental studies were conducted, more 'effects' were discovered that could be explained either through the same set of assumptions – a limited working memory and an effectively limitless long-term memory – or by modifying and extending these assumptions.

2.2.1 Summary

The limits of what is now described as working memory have been known since at least the 1950s. The importance of long-term memory to expertise has been known since at least the work of De Groot in the 1940s. From the 1980s onwards, a series of empirical studies began to draw upon the limits of working memory and the significance of long-term memory to explain a series of experimental findings in the field of educational psychology such as the goal free effect and the worked example effect.

2.3 Assumptions of Cognitive Load Theory

Cognitive Load Theory is an information processing theory of learning that seeks to explain how the information processing load induced by learning tasks can affect students' ability to process new information and to construct knowledge in long-term memory (Sweller, Van Merriënboer, & Paas, 2019). Cognitive Load Theory posits a model of the mind that consists of working memory and long-term memory (Sweller, Van Merriënboer, & Paas, 2019). The facets of human cognitive architecture that were discussed in Chapter 1 are foundational to Cognitive Load Theory. Learning is a change in long-term memory (Kirschner, Sweller, & Clark, 2006) and Cognitive Load Theory assumes that the purpose of instruction is to increase the amount of knowledge stored in long term memory (Sweller, Ayres, & Kalyuga, 2011).

Cognitive Load Theory is assumed to apply to biologically secondary knowledge rather than biologically primary knowledge. Biologically secondary knowledge is knowledge we have not had time as a species to evolve mechanisms for obtaining (Geary, 1995) such as knowledge of written language. Biologically secondary knowledge may be contrasted with biologically primary knowledge – knowledge that we have had time to evolve mechanisms for obtaining – such as knowledge of the local oral language or of how to navigate the local environment. Biologically primary knowledge is assumed to be transferred from the environment into long-term memory without being subject to the constraints of working memory (Sweller, 2008).

In contrast, biologically secondary knowledge is assumed to be first processed in working memory before passing into long-term memory and therefore it is subject to the constraints of working memory. As such, based on the known limits of working memory (Cowan, 2001), we would expect working memory to be able to process about four items of novel biologically secondary knowledge at a time. In contrast, knowledge held in long-term memory is not subject to these working memory constraints. We can posit either a discrete, separate structure called 'long-term working memory' to account for this (Ericsson & Kintsch, 1995), where, unlike regular working memory, items from long-term memory are processed without the limits imposed on items in regular working memory, or posit the more conventional view that schemas from long-term memory are effortlessly drawn into and processed in working memory. In the current context, these two models make identical predictions and so I will apply the concept of effortlessly processing these schemas in working memory in the following discussion.

The different properties of working memory and long-term memory, alongside the ability for schemas stored in long-term memory to be processed in working memory without known constraint, are embodied in the environmental organising and linking principle outlined in Chapter 1.

Cognitive Load Theory effects are the effects of different instructional procedures on learning i.e. the effects of different instructional procedures on the knowledge stored in long-term memory as quantified by subsequent assessments of this knowledge. A number of such effects have been identified and categorised since the 1980s and they are based upon replicable experiments conducted in many geographical locations by different teams of researchers (Sweller, Van Merriënboer, & Paas, 2019). Contrary to some perceptions, such experiments have been conducted in a range of settings including many studies – such as those described below – that have taken place in schools and with school-aged children (Martin, 2016).

Initially, Cognitive Load Theory effects were identified under a theoretical framework that did not specify a distinction between biologically primary and biologically secondary knowledge and that posited three sources of cognitive load: intrinsic, extraneous and germane. These three types of load were assumed to be additive. Intrinsic load was viewed as the load inherent in completing a task, extraneous load was viewed as unnecessary load produced by instructional procedures – such as attention drawn by an irrelevant picture – and germane load was viewed as the load devoted to the process of learning i.e. transferring knowledge from working memory to long-term memory. However, this formulation posed a problem in that it implied that as extraneous load decreased, germane load would increase and overall load would remain constant. This was falsified experimentally (Sweller, Van Merriënboer, & Paas, 2019).

Therefore, the relations between the types of load were reviewed, with only intrinsic load and extraneous load viewed as additive. Germane load was now viewed in terms of the switching of resources from extraneous to intrinsic load as extraneous load is reduced (Sweller, Van Merriënboer, & Paas, 2019).

In addition, when the first Cognitive Load Theory effects were being empirically identified, the concept of element interactivity was not yet established.

2.3.1 Summary

Cognitive Load Theory assumes that learning is a change in long-term memory and that biologically secondary knowledge must first be processed in working memory before passing into long-term memory. Furthermore, working memory is severely constrained, long-term memory is effectively limitless and the constraints imposed by working memory do not apply to schemas drawn from long-term memory into working memory for processing. Cognitive load must be optimised to stay within the constraints of working memory. Cognitive load may be intrinsic to the task or extraneous. A number of effects have been discovered that may be explained through the assumptions of Cognitive Load Theory.

2.4 Element interactivity

Much, but not all, biologically secondary knowledge is highly structured. For example, as discussed in Chapter 1, a simple algebraic equation such as $3x = 18$ contains four discrete elements – '3', 'x', '$=$', '18' – but these elements are also in a relationship with one another – they *interact* and so cannot be considered in isolation. To solve this equation, we may choose to divide by 3 in order to transform $3x$ to x. However, this has implications for the other side of the equation. Why? Because the $=$ sign is telling us that the left-hand-side of the equation has to be the same value as the right-hand-side. Therefore, if we divide the left-hand-side by 3 then we must also divide the right-hand-side by 3 in order to keep them equivalent. For a complete novice, the number of items to be simultaneously processed – '3', 'x', '$=$', '18', 'how do I transform $3x$ to x?', equivalence, that x represents an unknown number, divide both sides and so on, easily exceeds four items.

Importantly, '3', 'x', '$=$' and '18' are all intrinsic to the task. They are intrinsic sources of element interactivity. In a mathematical problem-solving situation, it may not be apparent to a learner that the solution requires dividing both sides of the equation, $3x = 18,$ by 3 and so the learner may search though a number of potential solution steps and their interrelationships prior to arriving at this equation. In this case, the problem-solving situation has supplied extraneous element interactivity. This is one reason why problem-solving imposes such a high cognitive load on novice learners.

Mathematical and chemical equations are perhaps the most transparent demonstration of the interdependence of elements – or 'element interactivity' (Sweller, 1993, 1994) – yet the same issue arises throughout the various domains of biologically secondary knowledge. For instance, in writing a paragraph for an essay, the paragraph must have a relationship to the overall essay, perhaps expanding upon a point raised in the introduction. Similarly, each sentence within the paragraph has a relationship with the others. The first sentence may be a topic sentence, explaining the paragraph's main thesis with the subsequent two sentences providing evidence for this point. In composing such a paragraph, a learner therefore must simultaneously process all of these elements and their relationships. It may be challenging and perhaps impossible to innumerate the elements and their interactions, but the principle of interacting elements remains.

Furthermore, the paragraph writing task could be made considerably harder in a number of ways. If the learner does not know the evidence to support the thesis then this may take the learner off into a search task. If the learner struggles with spelling or the formation of coherent sentences then these tasks will also consume working memory resources and will clearly be in an interdependent relationship with the elements previously discussed. This therefore illustrates that element interactivity is not a constant of a task or set of materials but that it is also dependent upon what schemas the learner has already acquired.

Chen, Kalyuga and Sweller (2017) expand upon this point to demonstrate that the expertise reversal effect (Kalyuga, Ayres, Chandler, & Sweller, 2003) described below can be explained through a combination of the effect of element interactivity and the acquisition of problem-solving schemas. Essentially, novices must process all elements and their interactions as items in working memory. Relative experts already have schemas in long-term memory which they may effortlessly draw upon to process many of these items, reducing the load on working memory. This is why, for instance, someone with training in algebra, when presented with $3x = 18$, will immediately be able to state $x = 6$ with little effort. This example also illustrates that schema activation is not the same thing as rote recall, if rote is defined as memorizing form in the absence of meaning (Willingham, 2002). The tasks of recalling that $7 \times 8 = 56$ or even that $18 \div 3 = 6$ could plausibly be envisaged as rote recall tasks, but being able to see the solution to $3x = 18$, requires the automation of generalisable solution methods.

It is important to emphasise that element interactivity is not synonymous with the volume of information to be learnt. Chen et al. (2017) draw the distinction between learning to solve an algebraic equation, such as the one described above, and learning the symbols of the periodic table of elements. Although the latter task contains a large amount of information, each symbol may be memorised discretely and sequentially. Learning the symbol for one element does not require the simultaneous manipulation of the symbol for a different element and so is not analogous to learning to solve algebraic equations. Therefore, even though a complex, time-consuming and challenging task, for a relative novice, learning the symbols of the periodic table would still be relatively low in element interactivity.

I have already delimited the predictions of Cognitive Load Theory to biologically secondary knowledge. When element interactivity is considered, it becomes apparent that many predictions based upon Cognitive Load Theory effects – such as that reducing extraneous load should lead to superior learning – only apply in situations of relatively high element interactivity. There are many situations in schools where learners are asked to learn relatively low element interactivity information such as dates of events, lists of vocabulary words and so on. Nevertheless, there are many learning situations that are relatively high in element interactivity and for which such heuristics would be appropriate.

2.4.1 Summary

Many, but not all, learning materials that involve biologically secondary knowledge, consist of elements that interact. With such materials, if a change is made to one element then this implies a change to another. Novice learners must therefore hold these elements *and their interactions* in working memory. However, once the relationships between these elements have been subsumed into a schema in long-term memory, they can be activated with no consequence to working memory load. Therefore, element interactivity – the number of interacting elements that must be process simultaneously in working memory – will depend upon both the nature of the learning materials and the level of expertise of the learner. Cognitive Load Theory implies that for relatively high levels of element interactivity, extraneous sources of cognitive load should be minimised.

2.5 Instructional effects of Cognitive Load

Cognitive Load Theory has formulated a number of instruction effects. Sweller, Van Merriënboer and Paas (2019) list seventeen such effects. These effects may be further classified as 'simple' or 'compound'. Simple effects are those that may be replicated in a given set of specific experimental circumstances whereas compound effects are those that act to modulate simple effects according to some additional factor. In the following, I will discuss only those effects that are relevant to this investigation.

2.5.1 Simple instructional effects

2.5.1.1 Goal Free effect

The goal free effect is a strategy for reducing cognitive load for novices encountering high element interactivity materials (Sweller and Levine, 1982). Learners are presented with, say, a geometrical diagram and are asked to find out any key information they can about the diagram rather than being asked to reach a specific goal of something to work out, such as the value of a given angle. Once given a goal, learners tend to use the strategy of means-ends analysis. This involves evaluating each attempted solution step to see whether it is a step toward the desired goal, building on it if it is and going back if it is not. Means-ends analysis therefore poses a heavy load on working memory (Sweller, 1988). In Productive Failure research, learners tend to be set a goal (Kapur, 2016) and that approach is replicated in this investigation. We would therefore expect the monitoring of progress towards these goals to consume cognitive resources.

2.5.1.2 Worked example effect

Worked examples provide a full problem solution for learners to study. When compared to providing the same problem for learners to solve, worked examples facilitate greater learning for relative novices. The effectiveness of worked examples was originally demonstrated in simple algebra problems (Sweller & Cooper, 1985) but the effect has been extended to a range of problem types including expository notes presented within the written text of a Shakespeare play (Oksa, Kalyuga, & Chandler, 2010). Worked examples reduce cognitive load by reducing problem-solving search by means-ends analysis and by drawing attention to salient features such that a learner is not required to assess a larger set of features and then discard those that are not relevant. As such, they reduce element interactivity by drawing upon the borrowing and reorganising principle of human cognitive architecture describe above. Worked examples may simply present the solution steps to a problem or may additionally present the rationale for the solution (Van Gog, Paas, & Van Merriënboer, 2008). They may also be modelled by a human (Hoogerheide, Loyens, & Van Gog, 2014). The explicit instruction phase of the empirical studies described in Chapters 4 and 5 makes use of human modelling of solution steps.

The active study of worked examples requires motivation on the part of learners – Cognitive Load Theory is not a theory of motivation and so begins at the point that motivation is present. If motivation is absent, worked examples will presumably not be given attention and so any worked example effect will presumably not eventuate. To aid motivation, studies have often presented worked examples alongside equivalent problems to solve in order to promote attention to the worked example (Sweller, Ayres, & Kalyuga, 2011). During human modelling, the kind of interactive strategies described by Rosenshine (2012) may help ensure attention to the worked examples. In Experiments 2-5 described in the empirical studies in Chapters 4 and 5, the explicit instruction phase is interactive and requires learners to periodically hold their calculators aloft for the instructor to review. The intention of requiring this action is to promote attention to the worked examples that are being modelled.

The worked example effect may be thought of as the central effect of Cognitive Load Theory. Failure to obtain the worked example effect in some situations – such as when text is not integrated with a diagram – has led to the establishment of other Cognitive Load Theory effects (Sweller, Ayres, & Kalyuga, 2011). The effect has also been used as evidence against the popular perception that instructional strategies that involve an element of discovery learning are superior (Kirschner, Sweller, & Clark, 2006).

2.5.1.3 Completion problem effect

Completion problems contain a partial solution that must be completed by the learners. They were introduced into Cognitive Load Theory in the context of partially completed computer programmes (Van Merrienboer & Krammer, 1990). Completing a problem allows fewer degrees of freedom and therefore narrows means-ends search compared with solving entire problems. Completion problems can be viewed in two ways. First, they can be seen as a strategy for ensuring attention to a worked example, as discussed above. Secondly, they can be viewed as a stage between studying worked examples and solving entire problems. As such, the completion problem effect is related to the guidance fading effect below.

In the empirical studies described in Chapters 4 and 5, some of the problem tasks are presented in partially complete form.

2.5.1.4 Split attention effect

The split attention effect arises when two sources of information that must both be attended to are presented separately. A typical example is a diagram labelled with points 'a', 'b', 'c', and so on with a key printed next to it explaining what these parts represent. This causes learners to split their attention between the two sources and imposes additional load. Tarmizi and Sweller (1988) found that physically integrating the information into the diagram was superior to presenting the two sources. Similar effects may be predicted for, say, attempting to learn the operation of a piece of hardware from a manual.

2.5.1.5 Redundancy effect

In contrast to the split-attention effect where two sources present *different information* that must be *integrated* by the learner, the redundancy effect occurs when two self-contained sources of the *same information* are presented simultaneously, such as when the same information is presented on both a diagram and in accompanying text. Chandler and Sweller

(1991) found that presenting learners with a diagram of blood flow in the body was superior to presenting the diagram alongside redundant explanatory text, presumably because the text-and-diagram condition imposed an additional load on learners – the load required to discover that the two sources contained the same information. Therefore, it is important when designing instructional materials such as those used in this investigation, to avoid simultaneously providing the same information. This includes instances where spoken and written text containing the same information may potentially be presented simultaneously (Kalyuga, Chandler, & Sweller, 2004). For instance, a PowerPoint slide containing information should not be presented alongside an oral statement of the same information. This appears to be counterintuitive for many teachers and conference presenters.

Furthermore, in Cognitive Load Theory, there is little to distinguish replicated information from the presentation of any other information that learners do not need to process. If, for example, a cartoon is presented alongside text but that cartoon is not necessary for comprehending the information in the text that the learner must attend to, the cartoon is redundant (Sweller, Ayres, & Kalyuga, 2011). Again, this principle must be respected in the design of instructional materials if they are to be optimal.

Note that both the split-attention effect and the redundancy effect, though quite different, can be obtained with similar looking materials. The difference therefore lies in the logical relationship between those materials.

2.5.1.6 Modality effect

In Chapter 1, we saw that models of working memory such as Baddeley's (1992) propose separate channels or components for dealing with visual versus auditory information. This suggests the possibility that these channels are independent and that we may therefore increase working memory capacity past Cowan's (2001) four items by presenting a mix of visual and auditory information.

Clearly, from the discussion above, such information should not be redundant. For example, if a diagram requires further explanation in order to be understood, we could take notice of the split-attention effect and integrate text into the diagram. Alternatively, spoken text could be presented with the diagram with the spoken text and the visual image being processed in separate, complementary channels of working memory. This could potentially be more effective than the physically integrated text due to the complementarity of the auditory and visual channels of working memory.

Mousavi, Low and Sweller (1995) demonstrates this effect, finding that, for learning from a diagram, spoken, non-redundant text was superior to integrated text. The modality effect has since been replicated in a range of different contexts (Ginns, 2005).

2.5.1.7 Variability effect

The variability effect is critical to understanding that cognitive load must be optimised rather than simply always reduced. Paas and Van Merriënboer (1994) demonstrated that for low cognitive load situations, such as learning from worked examples, a certain amount of variability in problem type is beneficial for learning and transfer of learning, presumably because it leads to the identification of relevant problem features. They found that this effect reversed for high cognitive load situations, such as learning from problem solving.

In Paas and Van Merriënboer's experiment, it is important to apprehend just what level of variability was introduced. In the low variability condition, for example, 19-23-year-old learners studied two examples of finding the distance between two points on a cartesian plane using Pythagoras' theorem before proceeding to further examples. In the high variability condition, the context and diagram were highly similar, but the second problem in the set had a different goal: given the distance between the two points, calculate the x-coordinate of one of the points. In both cases, the lines in the first two examples possessed conventional positive gradients. In contrast, a textbook for the current Victorian Certificate of Education course in Mathematical Methods (Evans, Wallace, Greenwood, & Lipson, 2015), intended for 16-17-year-old school students, introduces the same concept with a single worked example involving a negative gradient. It introduces it alongside a worked example for finding the midpoint of a line and then poses a number of problems for students to solve, some involving midpoints and some involving the distance between two points, although many of these are not supported by a diagram. Other problems in the set require considerable transfer such as: "There is an off-shore oil drilling platform in Bass Strait situated at D(0, 6), where 1 unit = 5 km. Pipes for this oil drill come ashore at M(−6, 1) and N(3, −1). Assuming the pipelines are straight, which is the shorter DM or DN?" which is presented without a diagram. Therefore, we should not overemphasise the variability of the problem sets that demonstrate the variability effect.

Note that variability increases cognitive load. However, it does so in a way that is relevant to problem solving and within the bounds of working memory capacity. It should also be expected to interact with expertise. As learners gain expertise, they develop schemas that result in previously high cognitive load, high element interactivity, learning situations reducing in element interactivity and therefore cognitive load. Greater variability may then be introduced.

2.5.2 Compound instructional effects

Compound instructional effects are effects that modify other Cognitive Load Theory effects and that often indicate the limits of other Cognitive Load Theory effects (Sweller, Van Merriënboer, & Paas, 2019). These are particularly relevant to the empirical studies described in Chapters 4 and 5 because the predictions of Cognitive Load Theory, based upon a number of Cognitive Load Theory effects, are tested in this investigation against contrasting predictions of Productive Failure theory that are discussed in Chapter 3.

2.5.2.1 Element interactivity effect

The element interactivity effect describes the finding that Cognitive Load Theory effects that may be found with high element interactivity may disappear or even reverse with low element interactivity. Element interactivity may be altered in two ways. Firstly, element interactivity may be altered by changes to the instructional materials that increase or decrease the elements to be simultaneously processed. For example, in Chen, Kalyuga and Sweller, 2015 and Chen, Kalyuga and Sweller (2016) a conventional worked example effect was found with novice learners for mathematical materials intrinsically high in element interactivity. However, for materials that were intrinsically low in element interactivity, a reverse of the worked example effect was found and a condition where learners were required to generate responses was found to be more effective. Similarly, Hanham, Leahy and Sweller (2017) experimentally manipulated element interactivity but in the context of teaching primary school students a structure for producing persuasive writing texts. In a low element interactivity condition, those learners who studied a worked example and then generated their own response to a similar prompt outperformed those who studied two worked examples, a finding consistent with the literature on the testing effect (see e.g. Karpicke, 2012). However, when element interactivity was increased by giving students additional categories of words to consider, the condition where learners studied two worked examples was superior.

Alternatively, element interactivity may be altered by increasing or decreasing the level of expertise of the learner. More expert learners possess more complete schemas relevant to the problem-solving situation and so can draw upon these as discussed above rather than needing to process all elements in working memory.

2.5.2.2 Expertise reversal effect

The expertise reversal effect can be considered a special case of the element interactivity effect (Chen, Kalyuga, & Sweller, 2017). From the 1970s onwards, Aptitude-Treatment Interaction studies (ATI) have found that less knowledgeable or able learners require more guided forms of instruction than their more knowledgeable or able peers (see e.g. Clark, 1982). A foundational experiment in the field of Cognitive Load Theory demonstrated that, for relative novices, studying worked examples had a superior effect on learning when compared to solving equivalent problems (Sweller & Cooper, 1985). This may be explained by the relatively high element interactivity involved when a novice solves an algebra problem such as the one discussed above – a problem that is typical of the kinds of problems involved in such studies. By presenting a worked example, many possible element interactions are removed and attention is focused only on those relevant to solving the problem. In contrast, it was found that when relative experts were presented with the same two tasks, studying worked examples or solving equivalent problems, the effect on learning was greater for solving problems than studying worked examples (Kalyuga, Ayres, Chandler, & Sweller, 2003). This can be explained if relative experts already possess relevant problem-solving schemas which can then be processed in their entirety as a single item in working memory rather than the multiple items a novice would need to process. In this case, studying worked examples would be redundant and the reduced cognitive load imposed by worked examples when compared to problem solving would be unnecessary. In fact, such worked examples could be a source of interference if, say, relative experts had learnt a slightly different but equivalent method of problem solving that had become encoded in the schemas they possessed. In contrast, solving problems would involve applying these schemas to new situations and act as a form of retrieval practice (Karpicke, 2012), strengthening the relevant problem-solving schemas.

2.5.2.3 Guidance fading effect

The guidance fading effect is implied by the element interactivity and expertise reversal effects. Whereas the expertise reversal effect operates along the axis of expertise, the guidance fading effect uses course duration as a proxy for expertise. Therefore, as a course of study progresses and learners move from novice to expert, the initial amount of guidance, such as the use of worked examples, can be reduced until a point when it may be more effective for learners to solve problems. Direct empirical evidence for the guidance fading effect has been obtained in controlled conditions where worked examples of geometry problems are gradually faded (Salden, Aleven, Renkl, & Schwonke, 2009), when scaffolds for writing scientific explanations are gradually removed (McNeill, Lizotte, Krajcik, & Marx, 2006), when metacognitive prompts for journal writing are gradually removed (Nückles, Hübner, Dümer, & Renkl, 2010) and a range of other contexts (Van Merriënboer & Kirschner, 2017). Although not directly relevant to this investigation, the guidance fading effect demonstrates further evidence for the robustness of the element interactivity effect.

2.5.2.4 Isolated elements effect

Some complex biologically secondary information that relative novices are required to learn contains more intrinsic elements than can be processed concurrently in working memory. One possible way around this difficulty may be to present elements or subsets of elements in isolation from the whole before bringing them together again. When learners are presented with individual elements to learn before being asked to integrate these into a whole then learning is superior to when they are presented with the entirety of the information (Pollock, Chandler, & Sweller, 2002). The empirical studies described in Chapters 4 and 5 do not attempt to make use of the isolated elements effect but it again demonstrates the robustness of the element interactivity construct.

2.5.2.5 Transient information effect

The transient information effect gives reason for caution when making use of transient sources of information, such as the use of spoken text to complement a diagram when taking advantage of the modality effect. Spoken language is transient because learners cannot refer back to it at a later stage, unlike a written text or visual image that may remain available. Other sources of transient information could include video clips or animations. If critical information is present in transient sources, this requires learners to hold this information in working memory, consuming working memory resources. Such an effect is therefore an important consideration whenever spoken text is used, such as in the investigations of this thesis. Leahy and Sweller (2011, 2016) found that short pieces of complementary audio-visual information were more effective than visual information alone but that this effect reversed for longer pieces of audio-visual information. Consequently, the transient information effect must be considered in constructing the explicit instruction component of the empirical studies described in Chapters 4 and 5.

2.6 Summary of Chapter 2

Cognitive Load Theory predicts that learning is maximised when extraneous cognitive load is minimised and intrinsic cognitive load is optimised. Extraneous cognitive load is generated by instructional materials or procedures and a range of effects have been established that vary instructional materials or procedures in order to minimise extraneous load. Element interactivity represents the number of interacting elements to be processed in completing a learning task. Element interactivity is both a property of the instructional materials and of learning materials and the learners. Relative experts possess relevant problem-solving schemas in long-term memory that can be activated and that therefore bypass the requirement to process all interacting elements in working memory. In order to optimise load, some instructional procedures increase intrinsic load by removing scaffolds for relative experts such as those demonstrating the expertise reversal and guidance fading effects. In some cases, such as the completion problem effect and variability effect, the removal of a limited number of scaffolds helps ensure learner attention to the problem situation without increasing load past the limit of working memory – approximately four items. In other cases, these effects represent intermediate stages of instruction as learners gain expertise.

Empirical studies suggest that many common instructional procedures for learning biologically secondary knowledge will overload the working memory of novice learners. This leads to the prediction that unguided exploration of a high element interactivity context would lead to little learning because it would consume all available working memory resources leaving nothing available for transferring knowledge to long-term memory. This contradicts the predictions of Productive Failure theory that will be explored in the next chapter.

Chapter 3
Productive Failure

The theory of Productive Failure suggests that a period of open-ended problem solving prior to explicit teaching may be superior to initiating instruction with explicit teaching.

According to this approach, Productive Failure may work to activate learners' prior knowledge, make learners more aware of knowledge gaps, increase awareness of deep structure and increase motivation. The research base is mixed, with some studies finding a positive effect for Productive Failure and some finding the reverse. However, only a subset of these studies vary just one factor at a time. These studies typically consist of two phases of instruction, explicit teaching and problem solving, with the order of these two phases reversed in the experimental and control conditions. Again, these provide mixed evidence for Productive Failure.

In contrast to the predictions of Productive Failure, Cognitive Load Theory suggests that explicit teaching prior to problem solving is superior because problem solving prior to explicit teaching would overload working memory.

3.1 Description of Productive Failure

Productive Failure is the conjecture that, "…leaving learners to struggle and even fail at tasks that are ill-structured and beyond their skills and abilities may in fact be a productive exercise in failure" (Kapur, 2008, p 380). Productive Failure proceeds through two phases. In the problem-solving phase, learners attempt to solve open-ended novel and complex problems. In the instructional 'consolidation' phase, learners are then explicitly taught the canonical solutions to the problems from the problem-solving phase (Kapur, 2016). Learners typically fail to solve the problems in the problem-solving phase, or at least fail to spontaneously generate the canonical solution, which is why the approach is termed productive 'failure'. For instance, Kapur (2014) presented 14-15-year-old learners with data on the number of points scored by two basketball players and asked them to determine which of the two players was the ‘most consistent’. The canonical solution, which none of the students in the Productive Failure condition independently discovered, was to compute standard deviation (in some near-replication studies, mean absolute deviation is used instead of, or in addition to, standard deviation (e.g. Loibl & Rummel, 2014a) and this is, logically at least, more discoverable by novices).

Kapur (2016) suggests that there are a number of design features that allow the effects of Productive Failure to be realised. These are that the problem is challenging, but not so challenging that a learner gives up; that there are multiple potential ways to tackle the problem; that the problem activates prior formal and intuitive knowledge; and that the teacher should build upon student-generated solution strategies and compare them with the canonical solution during the instructional phase.

Testing the Productive Failure hypothesis represents a challenge because it is difficult to design a fair test. The hypothesis suggests that the two phases of Productive Failure are superior to a single instructional phase, but an experiment that compared, say, the two Productive Failure phases, each of 20 minutes duration, against a single instructional phase of 20-minutes, would vary academic learning time simultaneously with instructional methods. Given the abundance of evidence for the salience of academic learning time (Brodhagen & Gettinger, 2012), we would not be able to attribute any effect to instructional methods alone. Similarly, simply doubling the length of the instructional phase in the control condition would mean that the two instructional phases were no longer directly comparable. One possible solution is a reversal of order, where problem-solving followed by instruction is compared with instruction followed by problem-solving. The control condition then represents something approximating explicit teaching as described by Rosenshine (2012).

3.2 Proposed mechanisms of action

Kapur (2016) proposed a number of reasons why problem solving first may be more effective than an approach that begins with explicit instruction. Problem solving first may activate and differentiate prior knowledge, and such activation may make learners more aware of the gaps in their prior knowledge. When presented with the canonical solution method, learners who have already attempted to solve the problem are able to compare their solutions with the canonical one, better enabling them to attend to critical features of the canonical solution. Finally, learners involved in problem solving first may be more motivated and engaged.

3.2.1 Activating prior knowledge

In schema theory, as described in Chapter 1, prior knowledge is assumed to reside in schemas held in long-term memory. Sweller, (1988) suggests that, "In order to acquire a schema, a problem solver must learn to recognize a problem state as belonging to a particular category of problem states that require particular moves. As a consequence, we might expect attention to problem states previously arrived at and the moves associated with those states to be important components of schema acquisition." (p. 261). Productive Failure may therefore have the potential to aid schema acquisition by drawing attention to problem states encountered during the problem-solving phase. However, it is not clear how the fact that such states are part of a non-canonical set of moves in the failure condition will affect the process of acquiring schemas for canonical problem-solving moves.

In addition, we might hypothesise that requiring learners to generate their own problem solutions prior to explicit guidance may strengthen the stimulus-response relation in memory in a similar way as has been proposed in order to account for the 'generation effect' (Slamecka & Graf, 1978; Hirschman & Bjork, 1988; Schwarz, Lindgren, & Lewis, 2009). This strengthening should lead to superior retention. However, it is worth noting that much of this literature involves learning relatively low element interactivity items, even for novice learners, such as lists of words. The role of generative learning is supported by some experimental evidence that suggests that generating failed solutions is superior to being exposed vicariously to failed solutions (e.g. Steenhof, Woods, & Mylopoulos, 2020).

Early problem solving may also be superior because explicit guidance may interfere with implicit learning (Reber, 1989) causing learners to focus on procedures rather than the situational structures that make the procedures useful (Schwartz, Lindgren, & Lewis, 2009). Productive Failure may therefore lead to superior transfer to new problems with a similar deep structure that are set in different contexts.

In my own teaching of mathematics, I am familiar with the issue of students learning problem solving moves for specific problem types in isolation but then, when sitting a synoptic assessment, not recognising which problem-solving moves to associate with each of a range of different problems. Therefore, an instructional procedure that would enhance the stimulus-response relationship between key problem features and appropriate problem-solving moves would be instructionally useful. If Productive Failure enhances these stimulus-response relationships then we may expect to see the signature of this in superior near transfer and possibly even far transfer.

Schwartz and Martin (2004) suggest that a problem-solving phase may activate specific kinds of knowledge and related schemas that are necessary for interpreting future procedural instruction. For instance, they suggest problem-solving may aid with drawing attention to the quantitative properties of a situation or the quantitative work a procedure will need to perform. In this way, they argue that a problem-solving phase acts as ‘preparation for future learning’.

3.2.2 Awareness of limits of prior knowledge

Learners who lack the knowledge to solve the problem, or, at least, to solve it canonically, may become aware of this, either through awareness of their failure in the problem-solving phase or when presented with the canonical solution in the instructional phase (Nachtigall, Serova, & Rummel, 2020). Failure to solve the problem in the problem-solving phase may prompt learners to ask additional questions, look for reasons why their approach did not work and for evidence to support these reasons (Tawfik, Rong, & Choi, 2015). During the instructional phase, a focus on erroneous learner solutions may cause learners to seek to resolve their failures and prepare them for the construction of new knowledge (Nachtigall, Serova, & Rummel, 2020). There is empirical evidence that open-ended problem-solving does indeed increase awareness of knowledge gaps (e.g. Glogger-Frey, Fleischer, Grüny, Kappich and Renkl, 2015). The key question is whether this impacts positively on learning.

Similarly, Schwartz and Martin (2004) argue that problem-solving phases prior to canonical instruction enable learners to let go of previous intuitions. This is similar to the concept of inducing 'cognitive conflict' (Festinger, 1957; Piaget, 1977). However, the view that cognitive conflict is necessary in order to induce 'nonmonotonic' change – the acquisition of new knowledge that requires learners to change or abandon aspects of previously learnt schemas – has been challenged by Ramsburg & Ohlsson (2016) who found little evidence in a review of the literature and who were able to induce a nonmonotonic category change in learners in the absence of cognitive conflict in a series of three experiments. These experiments also suggested the presence of cognitive conflict may even slow the learning process.

From a cognitive load perspective, metacognition of this kind, where learners pay attention to how successfully they are solving the problem and the possible reasons for this, would impose cognitive load and therefore require the availability of working memory resources. However, the means-ends analysis that learners would use in the problem-solving phase would be likely to have already consumed all working memory resources, given the complexity of the problems typically used, the novice status of the learners and hence the high level of element interactivity of the problems (see discussion in Chapter 2).

3.2.3 Awareness of deep structure

Problems contain both surface features and deep structure (Willingham, 2002). Chi, Feltovich and Glaser (1981) found that expertise was associated with recognition of deep structure. Advanced physics PhD students (experts) and undergraduate students (novices) were asked to classify physics problems. The experts classified the problems according to which physics principles were required to solve them whereas the novices classified them according to 'literal' features of the problems such as whether they involved a spring or an inclined plane. Logically, recognising deep structure should enable experts to solve problems that require similar solution methods but that are set in superficially different contexts. Therefore, the recognition of deep structure may be a valid goal of problem-solving instruction.

It has been hypothesised that presenting learner solutions alongside each other or alongside canonical solutions may help learners to apprehend this deep structure (e.g. Schwartz and Martin, 2004). Introducing the canonical methods after highlighting these different approaches may therefore enable learners to recognise the deep features of the canonical method from the outset (Loibl, Roll, & Rummel, 2017). However, it is not clear why a failed problem-solving phase is necessary for this to occur when an instructor could simply present contrasting solutions. There is, in fact, some evidence to support the value of presenting contrasting cases in the context of writing instruction (Lin-Siegler, Shaenfield, & Elder, 2015). However, Loibl, Tillema, Rummel and van Gog (2020) found no advantage in presenting contrasting cases in a study conducted in the context of statistics instruction.

If Productive Failure does differentially enhance learners' recognition of deep structure then this should again lead to a differential impact on near transfer.

3.2.4 Motivation

Another proposed mechanism of action for Productive Failure is the effect of the problem-solving phase on motivation. For instance, Russo & Hopkins (2019) argue that the challenging nature of a task presented prior to instruction may be more motivating than the less challenging nature of a task presented after instruction. Likourezos and Kalyuga (2017) suggest one goal of a problem-solving-first strategy may be the creation of a motivating environment that engages students. Moreno (2010) has proposed a cognitive-affective theory of learning that implies the incompleteness of arguments based solely upon cognitive load. This is because, "motivation determines the actual amount of cognitive resources invested in the learning task" (p. 137). It is therefore plausible that a learning task that is optimised for cognitive load but not optimised for motivation may be less effective at inducing learning than a task that is optimised for motivation but has a higher extraneous load. This may be because the greater investment of cognitive resources caused by the motivating task would more than compensate for the increased load. Productive Failure could potentially represent an example of such a task.

However, problem-solving more generally has been empirically associated with frustration and confusion (Di Leo, Muis, Singh, & Psaradellis, 2019). For Productive Failure specifically, there is not a large amount of empirical data on the impact on motivation. Glogger-Frey, Fleischer, Grüny, Kappich and Renkl, (2015) compared open-ended problem-solving with studying worked examples, each followed by explicit instruction, in the context of student teachers learning how to evaluate learning journals. They found that while transfer was better supported by worked examples, open-ended problem-solving was associated with greater curiosity and interest. However, we may expect differences in motivational profiles between those who have self-selected into a teaching course and are learning about learning journals and school students completing typical school-based tasks. Likourezos and Kalyuga (2017) administered a survey instrument to assess motivation to secondary school students learning geometry. The learners were randomly assigned to a worked example, partial guidance or no guidance condition prior to all groups learning from explicit teaching. There were few overall differences but some significant differences between groups on subscale items. These favoured the worked example condition, with, for example, a significant difference found between interest ratings in the worked example and unguided conditions. This evidence would seemingly contradict the view that Productive Failure is likely to be more motivating.

Motivation is a complex construct. For instance, a learner may find a concept or area of learning interesting, but still fail to invest cognitive resources if their perception is that they lack the skills to be successful. The potential for failure could be intrinsically demotivating for learners with an ‘entity theory’ of intelligence (Dweck, 2000), also known as a ‘fixed mindset’ (Dweck, 2008). Such learners believe intelligence is a fixed property of an individual and may avoid situations that involve failure because this will demonstrate a fixed lack of intellectual ability.

In addition, the longitudinal impact of motivation on achievement and achievement on motivation are unclear. Garon-Carrier, Boivin, Guay, Kovas, Dionne, Lemelin, Seguin, Vitaro and Tremblay (2016) tracked the intrinsic motivation of Canadian mathematics students through Grades 1-4 and found that achievement predicted later intrinsic motivation but intrinsic motivation did not predict later achievement. Intrinsic motivation was measured through responses to survey questions such as, "Mathematics interests me a lot." In contrast, Putwain, Becker, Symes and Pekrun (2018) found a reciprocal longitudinal relationship between enjoyment of mathematics and achievement in a sample of Grade 5 and 6 students in England. Whatever the precise nature of the relationship, both studies suggest no inherent conflict between maximising achievement and maximising motivation. However, the timescales involved in both studies are far longer that the timescale of a typical Productive Failure procedure.

3.2.5 Is failure necessary?

As the name implies, failure is integral to the concept of Productive Failure and many of the proposed mechanisms of action above rely on a failure to solve the initially presented problems, at least canonically. However, it is not clear whether such failure is necessary. Sinha, Kapur, West, Catasta, Hauswirth, & Trninic, (2020) constructed comparison conditions in which undergraduate students in a data science course were nudged either towards failure or success during a problem-solving phase prior to explicit instruction. Outcomes on measures of conceptual understanding were similar for both conditions.

3.3 Empirical evidence for Productive Failure[1]

A number of studies directly support the relative effectiveness of problem solving first when compared to an explicit instruction approach (e.g. Kapur, 2012; Loibl & Rummel 2014a, 2014b; Kapur 2014; Jacobsen, Markauskaite, Portolese, Kapur, Lai, & Roberts, 2017; Lai, Portolese, & Jacobson, 2017; Weaver, Chastain, DeCaro, & DeCaro, 2018; Halmo, Sensibaugh, Reinhart, Stogniy, Fiorella, & Lemons, 2020). A 2021 meta-analysis of 53 experimental and quasi-experimental studies showed generally positive effects for productive

[1] All of Section 3.3, apart from the discussion of Sinha and Kapur (2021), the first two paragraphs of section 3.4 and the 2nd, 3rd, 4th and 6th paragraphs of section 3.5 are taken directly from Ashman, Kalyuga and Sweller, 2019. Ashman contributed greater than 50% to the writing of this paper and these passages are reproduced with permission of the co-authors.

failure with heterogeneity for younger learners and for domain-general skills (Sinha & Kapur, 2021). In addition, studies have been conducted that do not directly reference an attempt to meet the Productive Failure criteria, but nonetheless suggest the relative effectiveness of an exploratory phase prior to direct instruction, when compared to direct instruction from the outset (e.g. Schwartz & Bransford, 1998; Schwartz & Martin, 2004; DeCaro & Rittle-Johnson, 2012; Schwartz, Chase, Oppezzo, & Chin, 2011).

In addition, Glogger-Frey, Gaus and Renkl (2017) found a positive effect for inventing over studying worked examples, potentially adding support to the predictions of Productive Failure. In this case, invention activities prior to a lecture led to superior transfer than studying worked examples prior to a lecture. The domain examined, the concept of density and ratio indices, and the invention activities that were used were similar to those used in the Schwartz et al. (2011) study. A key difference between Glogger-Frey et al., (2015) – which obtained a negative result for Productive Failure that will be discussed below – and Glogger-Frey et al. (2017) is that in the later study, learners were provided with additional practice activities. The additional practice given to learners in the 2017 paper should increase expertise and so decrease element interactivity.

Only a subset of studies demonstrating positive evidence for Productive Failure vary the order of instruction while varying nothing else (Loibl & Rummel, 2014b; Kapur 2014; Lai et al., 2017; DeCaro & Rittle-Johnson, 2012; Weaver, Chastain, DeCaro, & DeCaro, 2018). For instance, in the Schwartz et al. study (2011), while learners in both conditions received the same lecture at different times, the other tasks they completed were different in nature, and in the Jacobsen et al. (2017) study using a quasi-experimental design, different teachers taught the Productive Failure and explicit instruction conditions. Therefore, a factor was varied in addition to the order of instruction, and it may be this factor, or a combined effect of this factor and the order of instruction, that caused the outcome.

Where attempts are made to vary only the order of instruction, this may result in creating comparison conditions that lack ecological validity. For example, in Kapur's (2014) study, learners in the Productive Failure condition were compared with learners in a direct instruction condition. Learners in the direct instruction condition were first given instruction in the canonical solution method before being asked to spend a substantial amount of time solving a single problem in a number of different ways. This enabled a match to the problem-solving task given to the learners in the Productive Failure condition, yet it seems unlikely that a teacher would choose to follow such an approach. For instance, Rosenshine (2009) argued from the perspective of teacher effectiveness research that the most effective forms of explicit instruction guide learner practice and are interactive.

3.4 Empirical evidence counter to the predictions of Productive Failure

One of the simplest ways of varying the order of instruction while maintaining full and valid experimental control along with ecological validity is to compare studying worked examples followed by problem solving with exactly the same worked example and problem-solving phases but in reverse order. Thus, an example – problem sequence can be compared with a problem – example sequence with no other difference between groups. That comparison frequently has been made both in order to test the Productive Failure hypothesis (Hsu, Kalyuga, & Sweller, 2015) and for other, unrelated reasons (Leppink, Paas, Van Gog, Van der Vleuten, & Van Merrienboer, 2014; Van Gog, Kester, & Paas, 2011). In all cases, the example – problem sequence has proved superior to the problem – example sequence, in contradiction of the assumption that problem solving first is advantageous.

Other experimental studies have also looked for an advantage to learning from an initial exploratory phase prior to instruction and have either found a null result or an effect in the opposite direction (e.g. Fyfe, DeCaro, & Rittle-Johnson, 2014; Rittle-Johnson, Fyfe, & Loehr, 2016). In addition, Glogger-Frey, Fleischer, Grüny, Kappich, & Renkl (2015) compared an exploratory phase with studying worked examples, prior to instruction in the domains of education and physics and found that transfer was better supported by studying worked examples in both domains. Similarly, Cook's (2017) experimental study found evidence that studying worked examples prior to explicit instruction was superior to a Productive Failure condition for undergraduate biology students learning statistical methods. Worked examples are a form of explicit instruction and so these studies do not support the predictions of Productive Failure.

Nachtigall, Serova and Rummel (2020) tested the specific predictions of Productive Failure in the domain of social science using a quasi-experimental design that varied the order of instruction and in which the authors attempted to replicate the optimal design features for Productive Failure as described above. In contrast to the predictions of Productive Failure, there was no advantage to problem-solving prior to explicit instruction. Similarly, Loibl, Tillema, Rummel and van Gog (2020) conducted a randomised controlled trial that varied the order of instruction for secondary students learning about the mathematical concept of variance. They also varied the provision of contrasting cases in the problem-solving phase, a proposed design feature conducive to Productive Failure, via a 2×2 experimental design. The provision of contrasting cases had no effect on the results, with the students who received explicit instruction prior to problem solving demonstrating greater procedural fluency and no difference between the conditions on conceptual understanding.

3.5 Conceptual versus procedural knowledge

This leads to one further consideration that arises from the research into Productive Failure – the differential impact on procedural knowledge versus conceptual knowledge.

DeCaro and Rittle-Johnson (2012) observed a problem solving first advantage for conceptual knowledge but not for procedural knowledge. In their case, conceptual knowledge involved understanding the principle of equivalence - that the equal sign in mathematical questions (i.e. '=') means 'the same as' and not 'put your answer here'. Although it is a fundamental concept, the tasks associated with this concept may have been relatively low in element interactivity compared to the tasks associated with procedural knowledge that usually involve a series of interrelated steps. For instance, one question involved recalling three equations after a five second delay, whereas another question required the recall of a definition of the equal sign. Other studies (e.g. Kapur, 2014) demonstrated similar findings, replicating a difference favouring problem-solving first on conceptual but not procedural knowledge. Together, these findings may be explained by element interactivity that is likely to be relatively lower for conceptual than procedural knowledge.

Crooks and Alibali (2014) conducted a review of the construct of conceptual knowledge in the mathematics education literature. They noted that conceptual knowledge is often left undefined or is vaguely defined and that the tasks designed to measure conceptual knowledge do not always align with theoretical claims about mathematical understanding. For instance, their review found that the most common conceptual task in the literature on mathematical equivalence involved providing a definition of the equal sign, as in the DeCaro and Rittle-Johnson (2012) study.

The extent to which such recall tasks reflect genuine differences in conceptual knowledge is therefore unclear. Presumably, we could teach a learner to recall a definition and yet not claim, with certainty, that the learner understands what it means. A superior measure of conceptual understanding may therefore be near transfer because near transfer requires learners to apprehend a problem's deep structure. Transfer represents more meaningful learning because it demonstrates that learners have understood the concepts (Mayer, 2002).

A further development relevant to the discussion of procedural versus conceptual knowledge has been the extension of the concept of Productive Failure to a process known as 'micro Productive Failure'. This was formulated by Ziegler, Trninic, & Kapur (2021) in response to the inconsistent effect of Productive Failure on the acquisition of procedural knowledge. Instead of inventing solutions to a whole problem, a series of brief periods were employed where learners attempt to invent solutions to algebraic steps such as simplifying the expression '$3bc + bc + 6bc$' in order to obtain '$10bc$', before being explicitly taught the correct procedure. This was contrasted with a comparison condition where students were first explicitly taught the procedure before practising it i.e. the same tasks in a different order. Micro Productive Failure was found to be superior to explicit teaching first. Participants were sixth grade students from Switzerland. Although they generally failed to invent the correct solutions in the Productive Failure condition, they would likely have had prerequisite knowledge of $3 + 1 + 6 = 10$ and the addition of various units such as $\$3 + \$1 + \$6 = \$10$ (see analysis of various European – although not Swiss – curricula in Mullis, Martin, Goh, & Cotter, 2016). Therefore, this intervention would have involved learning a single element such as 'treat bc as a unit' and would therefore have been low in element interactivity.

This perhaps highlights the fact that procedural knowledge and conceptual knowledge do not directly map onto high a low interactivity (or the reverse) and, instead, it is necessary to examine exactly what each task involves. Rather than a differential effect on procedural versus conceptual knowledge, we should perhaps examine a differential effect on low versus high element interactivity tasks.

3.6 Conflict with predictions of Cognitive Load Theory

Cognitive Load Theory predicts that novices would learn more from an explicit instruction followed by problem solving sequence than from a problem solving followed by explicit instruction sequence when learning how to solve the kinds of problems typical of the Productive Failure literature that are relatively high in element interactivity. This prediction would not hold for relative experts and it would not hold if the learning objective required the memorisation of simple, non-interacting facts such as a number of symbols or a set of dates. In both these latter cases, element interactivity would be low. In the case of a relative expert, this would be because they possess relevant schemas in long-term memory that can be drawn into working memory effortlessly, and so all of the elements of the problem would not need to be manipulated in working memory. In the case of non-interacting facts, the single element needed to be manipulated at any time would be within the capacity limits of working memory.

In contrast, dealing with ratios representing density (Schwartz & Martin, 2004) or determining standard deviation (Kapur, 2014) requires the manipulation of multiple interacting elements by novice learners. Typically, these learners do not possess relevant schemas in long-term memory – this is an explicit assumption of Productive Failure, otherwise we would not expect learners to fail. In addition, such tasks typically have a clearly articulated goal. This will induce learners to use means-end analysis which again consumes working memory resources (Tricot & Sweller, 2014). An interesting variation would therefore be for Productive Failure theorists to set a goal-free problem in the problem-solving phase and this could be an avenue for future research.

In the context of the current investigation, Productive Failure theory predicts that if the conditions for Productive Failure – such as comparing learners' naïve solutions with the canonical solution – are reproduced, then problem solving prior to explicit instruction should lead to superior learning outcomes, although this may only become apparent for near-transfer tasks.

Alternatively, according to Cognitive Load Theory, there should be no advantage for problem solving prior to explicit teaching and we should expect explicit teaching prior to problem solving to be superior on similar tasks and near-transfer tasks.

3.7 Summary of Chapter 3

Productive Failure is the proposition that attempting and failing to solve a problem canonically, prior to explicit instruction in the canonical method has learning benefits for novice learners that are superior to explicit instruction from the outset. Productive Failure therefore proceeds in two phases – a problem solving phase followed by an explicit instruction phase.

Several conditions have been suggested for achieving this Productive Failure effect. They include that the problem is challenging but not so challenging that a learner gives up, that there are multiple ways to potentially tackle the problem, that the problem activates prior formal and informal knowledge and that the teacher builds on student solutions in the subsequent instructional phase.

In addition, a number of proposals have been advanced for mechanisms of action. Productive Failure may activate prior knowledge by focusing attention on problem states, by strengthening stimulus-response relationships or by focusing learners on situational structures rather than procedures. Productive Failure may increase learners' awareness of gaps in the prior knowledge which, once identified, may prepare them better for explicit instruction. Productive Failure may increase awareness of deep structural features of a problem rather than surface features, aiding transfer. Finally, Productive Failure may simply be a more motivating form of instruction that therefore stimulates the investment of cognitive resources.

However, many of these proposed mechanisms do not take account of cognitive load and depend upon metacognitive resources that Cognitive Load Theory would predict are already being consumed by problem solving. Moreover, there is little evidence to demonstrate Productive Failure's motivational effect and it is an active question as to how necessary it is for learners to fail in the problem-solving phase, with one recent study showing a similar effect for scaffolded success.

It is difficult to provide a fair and ecologically valid experimental test of Productive Failure. A number of studies support the effectiveness of the problem solving – explicit instruction sequence but only a subset of these vary just one factor at a time. Those that vary one factor at a time test a problem solving – explicit instruction sequences against precisely the same phases in the reverse order. Some use worked examples as the explicit instruction phase and some use regular instruction.

A number of similar experiments that also vary one factor at a time did not find a Productive Failure effect.

One question that arises from these studies is the differential effect on procedural versus conceptual knowledge, with some limited evidence for an increased effect of Productive Failure on conceptual knowledge. However, conceptual knowledge is not well defined in the literature and can often involved learners in effectively recalling a definition. Recalling a definition is a low element interactivity task even for novice learners and so this would be consistent with effects such as the generation effect that find a problem-solving first advantage for learning low element interactivity material.

Rather than conceptual versus procedural knowledge, a better conceptualisation may therefore be between low element interactivity and high element interactivity learning.

Cognitive Load Theory predicts that for high element interactivity learning objectives, explicit instruction followed by problem solving would be superior to the reverse order. This should be demonstrated by assessments on procedural knowledge but not necessarily conceptual knowledge which is poorly defined and often low in element interactivity. A better secondary test may therefore be a test of near transfer because both the proposed mechanisms of action for Productive Failure and Cognitive Load Theory predict superior near transfer, albeit for different groups.

Chapter 4
Introduction to empirical studies

To test the competing predictions of Productive Failure and Cognitive Load Theory, the context of instruction in the energy efficiency of light globes with upper primary school students was selected. Element interactivity was a critical consideration within this context and an experimental design needed to be developed that would vary only one factor at a time.

4.1 Selection of context

Much of the research in Productive Failure and related invention literature has involved mathematical concepts such as standard deviation (e.g. Kapur, 2014), although some studies have explored physical concepts such as density (e.g. Schwartz, Chase, Oppezzo, & Chin, 2011) and even educational contexts such as learning strategy-evaluation (Glogger-Frey, Fleischer, Grüny, Kappich, & Renkl, 2015). Density requires an appreciation of a proportion i.e. the relationship between two linked quantities. This creates a base level of element interactivity for novice learners of at least three items – the two quantities and their relationship. Comparisons between different densities then require learners to process yet more elements. Standard deviation is arguably even higher in element interactivity, drawing upon concepts such as deviation – the difference between two numbers – and mean, but of course, element interactivity always depends heavily on learner prior knowledge.

For the following empirical studies, the context of the energy efficiency of light globes was selected. This involves applying a mathematical model to a basic physics context. Given the current context in which governments and consumers are increasingly conscious of the need for energy efficiency, this was viewed as both valuable as a scientific concept and a valuable component in enabling learners to think critically about energy efficiency.

During the course of the empirical studies, it became apparent that calculating the energy efficiency of light globes is relatively high in element interactivity for novice learners. At base, it imposes a load similar to that of the concept of density, in that useful energy output is compared to energy input in the form of a percentage. Different globes are then compared. Through the studies, various manipulations were used. For example, in some experimental materials and post-test questions, wasted energy output was provided to learners but not useful energy output. This then required learners to calculate the latter using the law of conservation of energy. Such manipulations were therefore capable of further altering the element interactivity of the tasks.

Typically, such a context would be taught in middle school science. Learners were selected such that they had not previously learnt about energy efficiency. This requirement, coupled with an increasingly ambitious middle school science programme in the lead investigator's school where the study was conducted led to the selection of students in Years 5 and 6 to take part in the study i.e. the final two years of primary school.

4.2 Experimental design

The need to vary only one factor at a time led to an experimental procedure in which learners were randomly allocated to one of two conditions and the order of instruction was manipulated between conditions in order to compare problem solving followed by explicit instruction with explicit instruction followed by problem solving. This was the same approach taken by studies discussed in the previous chapter that varied only one factor at a time.

In Experiment 1, the explicit instruction condition consisted of a video of a PowerPoint Presentation in order to ensure all learners had the same explicit instruction. However, this approach introduced methodological problems, such as the lack of interactivity in the explicit instruction condition, discussed more fully in the next chapter.

As a result, for Experiments 2-5, an innovative approach was used. The decision was made to switch from a video presentation to a 'lecture' consisting of live, interactive explicit teaching. This then introduced the issue of how to ensure that the lecture was the same across both conditions and the potential confound that would be introduced if it was not.

To resolve this issue, it was decided to expose all students in both conditions to the same lecture. This was achieved through several design features. A reading filler task of equal duration to the problem-solving task staggered the two conditions. The reading task was set in the science domain but was unrelated to energy efficiency calculations. The study was conducted in an auditorium that could accommodate all students in both conditions simultaneously. Learners placed in each condition were seated in alternating rows in the auditorium.

In the problem solving – lecture condition, learners first completed a problem-solving booklet containing the relevant energy efficiency problems. They then participated in the interactive lecture along with students in the other condition. Interactivity was provided by requiring learners to hold their calculators aloft once when they had completed each calculation. Finally, learners in this condition completed the reading filler task.

In the lecture – problem solving condition, learners first completed the reading filler task i.e. at the same time that learners in the other condition completed the problem-solving booklet. They then participated in the same interactive lecture as learners in the other condition. Finally, learners in this condition completed the problem-solving booklet.

An immediate post-test was avoided in favour of a test taken in the learners' next science lesson (Day 2 of the study).

This approach is summarised in Figure 4.2.1

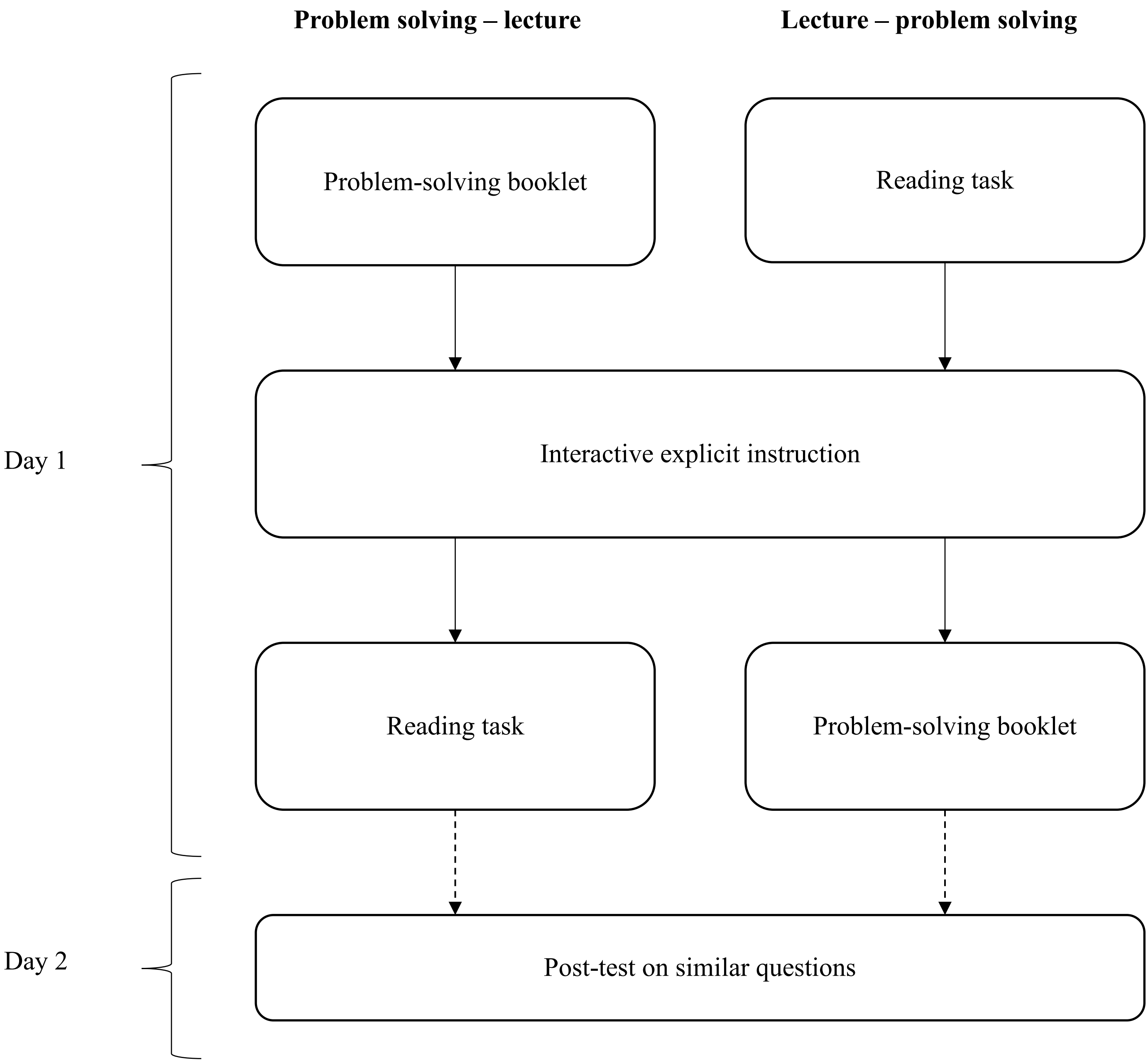

Figure 4.2.1

This design introduced the potential confound that not all students completed the relevant aspects of the study in exactly the same window of time. One reason the post-test was delayed was to minimise the impact of this.

4.3 Research Questions

Initially, the main research question was simply: which condition will lead to the best performance on a post-test? However, with refinement, it was established that the initial range of tasks required of students on the post-test was wide and of varying amounts of element interactivity. The experimental materials were therefore progressively refined to focus solely on the calculation of energy efficiency and the subsequent comparison of light globes, with a two-component post-test developed representing highly similar and near transfer problems respectively. The focus on this relatively high element interactivity learning task narrowed the scope of the research questions to: which condition will lead to the best performance on similar tasks when element interactivity is high?; and which condition will lead to the best performance on near-transfer tasks when element interactivity is high?

Finally, by introducing additional procedural steps in order to further increase element interactivity, this introduced the additional research question: what is the effect of relative differences in element interactivity on performance in the similar tasks and the near-transfer tasks?

Due to the difficulty of obtaining suitable definitions of conceptual knowledge identified by Crooks and Alibali (2014), performance on transfer tasks was chosen as a proxy for conceptual knowledge rather than attempting to directly assess conceptual knowledge.

4.4 General Hypotheses

The hypotheses were based on the research questions. Initial, general hypotheses were simply drawn from the two competing theoretical models, Cognitive Load Theory and the Productive Failure literature:

- H1: There would be a Productive Failure effect where learners would learn more from problem solving prior to explicit instruction

- H2: Problem solving prior to explicit instruction would overwhelm working memory and learners would learn more from explicit instruction prior to problem solving

With respect to the role of element interactivity, the hypotheses narrowed to: explicit instruction first is superior to problem solving first using high element interactivity information and that this would be apparent in similar tasks and near transfer tasks.

4.5 Summary of Chapter 4

The context of the efficiency of light globes was selected to test the competing predictions of Productive Failure and Cognitive Load Theory. This context is both valuable in its own right and valuable as a component of thinking critically about a significant contemporary issue. Year 5 and 6 students were selected because they would not have learnt these concepts before. An innovative experimental procedure was developed to ensure all students across the two comparison conditions received the same interactive explicit teaching. The context of calculating efficiency is relatively high in element interactivity and as the empirical studies progressed, drew towards a narrowing of the research questions and hypotheses to relate only to high element interactivity tasks. Even so, element interactivity was manipulated.

Chapter 5
Empirical Studies

A series of five experiments was conducted to test competing hypotheses produced by Productive Failure theory and Cognitive Load Theory. The first three experiments essentially refined the experimental method to be used, with the role of element interactivity becoming more apparent as the experiments progressed. The results of the final two experiments were consistent with the hypothesis informed by Cognitive Load Theory in the context of learning how to solve relatively high element interactivity isomorphic problems. For the highest element interactivity condition, Experiment 4, this result was extended to problems involving near-transfer. No significant results were consistent with the hypotheses informed by Productive Failure theory. This may be due to Productive Failure effects not extending to high element interactivity tasks.

5.1 Experiment 1

The purpose of this experiment was to determine whether explicit instruction prior to problem solving was superior to problem solving prior to explicit instruction in the context of learning how to determine the efficiency of different electrical devices. Given that this was the first in a series of planned experiments, a secondary purpose was to refine materials and experimental techniques for future experiments.

There were two competing hypotheses:

- H1: There would be a Productive Failure effect where learners would learn more from problem solving prior to explicit instruction
- H2: Problem solving prior to explicit instruction would overwhelm working memory and learners would learn more from explicit instruction prior to problem solving

5.1.1 Method

5.1.1.1 Participants

The participants were 48 Year 6 students from an independent school in Victoria, Australia. They were approximately 11 years old and had not previously received instruction in conservation of energy or the related concept of efficiency. An entire cohort of Year 6 students were invited to participate and all students who had returned consenting ethics approval forms and who were present on both days of the experiment were included in the sample. The students were randomly assigned to either the group that received explicit instruction first or the group that received problem solving first. Prior to the study, approval was obtained from the Human Research Ethics Advisory Panel of the University of New South Wales.

5.1.1.2 Materials

Learners were asked to solve a variety of problems involving conservation of energy. A typical problem involved learners being given the electrical energy used by a number of electrical devices per minute (e.g. a series of different electric fans) and the energy wasted by each device per minute as heat and sound. Learners were required to calculate the useful energy output of the device and then use this value and the energy used by the device to calculate its efficiency. Learners were then asked to decide which was the most efficient device in the list. An example question is show in Table 5.1.1. Appendix 1 provides the full set of materials used.

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)
A	500	200
B	500	300
C	800	200
D	800	400

Which model of fan is the most efficient?

A B C D

Table 5.1.1 Example of a question used in Experiment 1.

However, not all of the questions were of the same type. Each drew on the same principles but had different surface features. The types of devices changed and the way the information was presented changed. For instance, Figure 5.1.1 shows how similar information was represented graphically

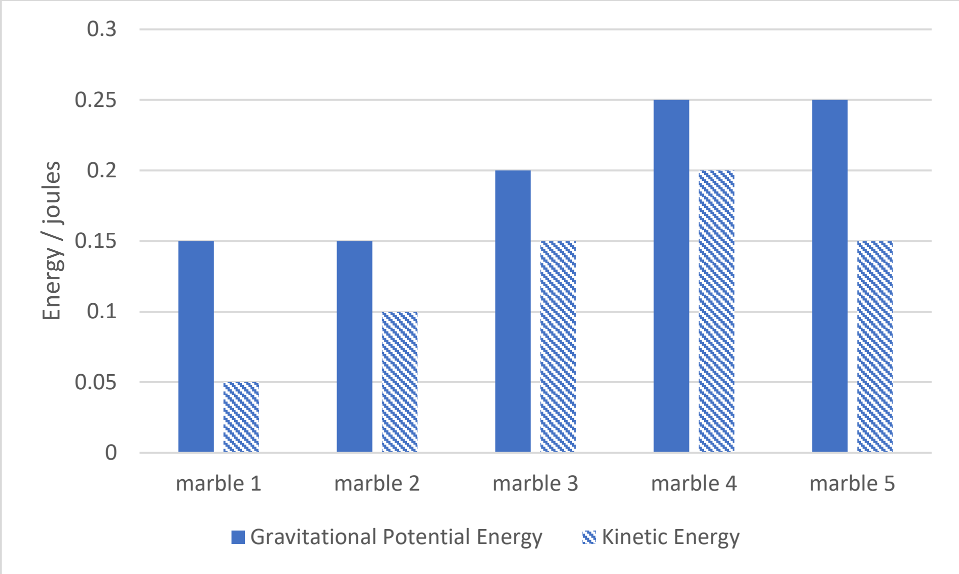

Figure 5.1.1 In this question, different marbles are dropped from different heights and the graph shows the initial gravitational potential energy (the input) alongside the final kinetic energy (the useful output).

Element interactivity was not controlled in the design of Experiment 1 and varied across problems. However, element interactivity for these problems was relatively high. For instance, consider the question outlined in Table 5.1.1. Firstly, learners must subtract (1) heat and sound energy (2) from electrical energy (3) to obtain kinetic energy (4). Learners then need to identify the input energy (5) identify the output kinetic energy (6) divide the output kinetic energy by the input energy (7); multiply by 100 to complete the percentage calculation for each fan from these two numbers (8); repeat for each globe (9,10,11); identify the lowest percentages (12), resulting in twelve interacting elements, a number considerably above the current assumptions of a working memory limit of four or fewer elements when processing information (Cowan, 2001).

The questions were designed so that they would be meaningful and make intuitive sense to learners without any prior instruction in the area and the solution method. Accordingly, terms like ‘power’ and ‘efficiency’ were avoided in the wording of the questions. Instead, learners were asked to identify, for example, which light globe was the most “energy saving”. The questions also allowed learners to attempt different solution methods, consistent with design features associated with a Productive Failure effect (Kapur, 2016).

Five questions were compiled into a problem-solving booklet. An additional 12 questions were compiled into a post-test booklet. These were similar in nature. A number of questions had a similar structure to the question in Table 5.1.1. However, there were no graphical representations of the data as in Figure 5.1.1. In addition, there were a number of simpler multiple-choice items in the post-test that probed underpinning concepts such as the physical law of the conservation of energy. Figure 5.1.2 is an example of such a question:

Question 2
What is the best description of what happens as an object falls? (please circle)

A. It loses kinetic energy

B. It gains gravitational potential energy

C. It loses elastic potential energy

D. It loses gravitational potential energy

Figure 5.1.2 A multiple-choice question probing an understanding of the law of conservation of energy.

In total, the post-test contained eight of the simpler multiple-choice questions and four of the more complex questions involving data presented in tables. The questions with tables had spaces available for the missing values so that students could calculate these values and add to the table. Questions 9-11 also employed multiple-choice responses where learners were asked to identify e.g. which device produces the least amount of useful energy or which device is the most efficient. For the final question, students were simply asked to fill in all of the missing values. Each of the four columns had some missing values.

The explicit instruction component was by means of a PowerPoint presentation which was recorded as a video and made available to participants via a laptop computer. The final video was five minutes and 32 seconds in duration and was silent, with the instruction being delivered by animated text. The video instructed learners in the names of different types of energy, the principle of the conservation of energy, the concept that a 'machine' is any device that transforms energy from one type into another and the method for solving problems similar to the problem in Table 5.1.1.

5.1.1.3 Procedure

The experiment took place during the learners' regular science lessons. Learners were randomly assigned to one of two conditions; Problem solving – lecture (26 learners) and Lecture – problem solving (22 learners). The difference in numbers resulted from the fact that randomisation took place prior to all ethics approval forms being returned along with a differential effect of students being withdrawn for individual music lessons. Each learner was issued with a basic calculator.

Two classrooms were used, one for each condition. Students were then assigned to the relevant classroom. The experiment was supervised by the teachers who would normally teach this cohort of students with one teacher supervising each classroom. Each teacher was provided with a script to read out to the learners to introduce the task. This briefly explained the task, reminded students that it did not count towards internal grades and that they should just try to do their best.

In the Problem solving - lecture classroom, learners completed the problem-solving booklet for 10 minutes and then watched the video on a laptop that they were each provided with. In the Lecture - problem solving classroom, learners completed the same tasks in the reverse order. Three days later, again during their regular science lessons, learners completed the post-test for 15 minutes under normal assessment conditions i.e. no discussion of the questions with peers.

5.1.1.4 Scoring

Questions 1-8 were simple multiple-choice questions. A correct choice scored 1. In Questions 9-11 there was one mark available for correctly calculating the values in each of the two missing columns and one mark available for selecting each correct multiple-choice response. In the final question, there was one mark available for each correctly completed column of the table. Items on the post-test component had low reliability with Cronbach's α=.41.

5.1.2 Results

Means and standard deviations for the post-test scores are presented in Table 5.1.2. Learners in the Lecture - problem solving condition who received explicit instruction first, scored similarly to learners in the Problem solving - lecture condition who received problem-solving first, $t(46)=0.77$, $p= .45$.

	Problem solving-Lecture (*n = 26*)	*Lecture-Problem solving* (*n = 22*)
Post-test (*Total 23 marks*)	9.15 (3.12)	8.27 (4.04)

Table 5.1.2. Means and standard deviations (in brackets) for the post-test in Experiment 1.

A visual representation of the data is presented in Figure 5.1.3 (Ho, Tumkaya, Aryal, Choi, & Claridge-Chang, 2018).

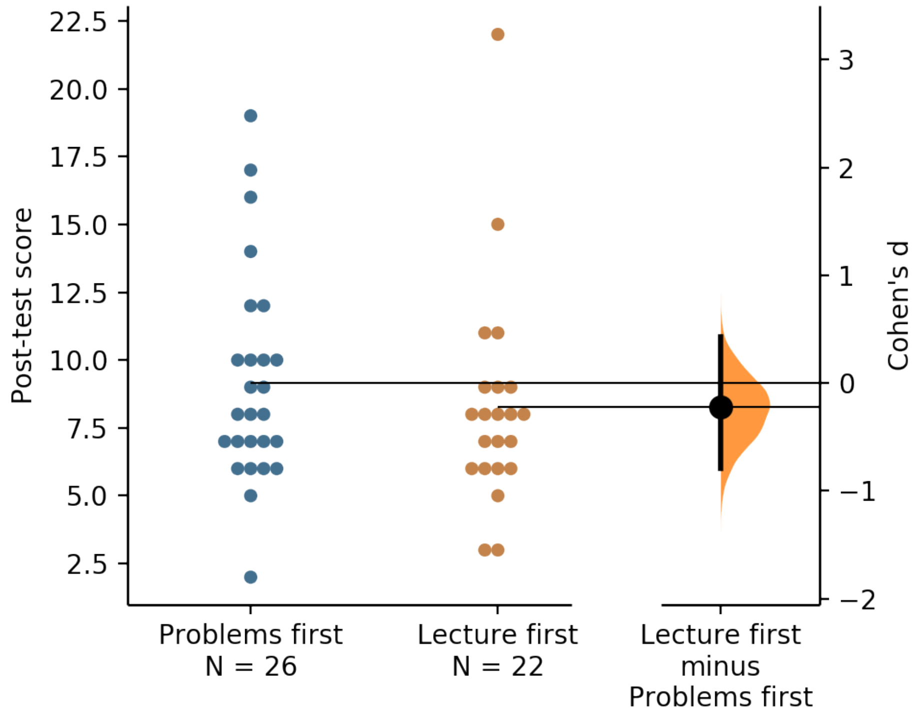

Figure 5.1.3 The Cohen's d between Problems first and Lecture first is shown in the above Gardner-Altman estimation plot for Experiment 1. Both groups are plotted on the left axes; the mean difference is plotted on a floating axis on the right as a bootstrap sampling distribution. The mean difference is depicted as a dot; the 95% confidence interval is indicated by the ends of the vertical error bar.

5.1.3 Discussion

It is apparent from the data that few students learnt the required concepts. The total for the post-test was 23 and yet the means for the Problem solving - lecture condition and the Lecture - problem solving condition are 9.15 and 8.27 respectively. Moreover, the post-test contained simple items that did not require use of the efficiency calculation. A major limitation of this experiment is that it addressed many concepts simultaneously. The explicit instruction of roughly five-and-a-half minutes addressed not just efficiency calculations but many other underlying principles and the post-test then sought to assess these principles in addition to the efficiency calculations. The assessment of multiple constructs is clearly reflected in the low Cronbach's α value of .41.

There were also problems with enacting the procedure. The two teachers leading the two different conditions were observed. The teacher who led the Lecture - problem solving condition simply read out the script as requested and then the students completed the tasks. However, the teacher in the Problem solving - lecture condition gave a long, impromptu address involving a discussion of the nature of scientific research and additional reassurances about the irrelevance of student performance to progress in science. Not only does this mean that affect is likely to have varied between the two conditions, the length of the address meant that learners in the Lecture - problem solving condition had nearly completed the experiment before learners in the Problem solving - lecture condition began. These confounds may or may not have affected the results of the experiment.

Finally, there was no mechanism for ensuring attention to the explicit teaching video and this may also have affected performance.

5.2 Experiment 2

The purpose of this experiment was the same as for Experiment 1: to determine whether explicit instruction prior to problem solving was superior to problem solving prior to explicit instruction in the context of learning how to determine the efficiency of different electrical devices. The main change from Experiment 1 was a change to the experimental procedure to mitigate a number of issues identified in Experiment 1.

The two competing hypotheses were identical to Experiment 1.

5.2.1 Method

5.2.1.1 Participants

The participants were 72 Year 5 students from an independent school in Victoria, Australia. They were approximately 10 years old and had not previously received instruction in conservation of energy or the related concept of efficiency. An entire cohort of Year 5 students were invited to participate and all students who had returned consenting ethics approval forms and who were present on both days of the experiment were included in the sample. The students were randomly assigned to either the group that received explicit instruction first or the group that received problem solving first. Prior to the study, approval was obtained from the Human Research Ethics Advisory Panel of the University of New South Wales.

5.2.1.2 Materials

Learners were asked to solve a variety of problems involving conservation of energy. A typical problem involved learners being given the electrical energy used by a light globe and the energy wasted by the light globe per second as heat and sound. Learners were required to calculate the useful energy output of the device and then use this value and the energy used by the device to calculate its efficiency. Learners were then asked to decide which was the most efficient device in the list. An example question is show in Table 5.2.1. Appendix 2 provides the materials used in the presentation, problems solving task and post-test. Appendix 6 provides the materials for the reading task.

Anita wants to replace the old light globes in her lounge room with new energy saving globes. She may choose to use more globes or fewer globes in order to keep the amount of light the same.

Light globes take in electrical energy and give out heat and light energy.

Anita has the following information that she can use to make her choice between Globes A, B and C. The amount of energy is measured in joules which have the symbol 'J'.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 J	15 J	15 J
B	20 J	8 J	12 J
C	30 J	18 J	12 J

Which globe should she choose?

Why should she choose this globe?

Table 5.2.1 An example of a question used in Experiment 2

These questions were compiled into a problem-solving booklet and a set of questions to be used as the post-test. The questions were more isomorphic than in Experiment 1. For each question, data on total energy used and energy output was presented in a table. However, the type of electrical device varied and the completeness of the data presented in the table varied. Some questions presented all of the data as in Table 5.2.1, some omitted the useful energy given out, requiring learners to calculate this and the final question presented a table where, for each device, one of the three data points was omitted as in Table 5.2.2.

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Below is some information about different types of fan.

Some of the information is missing.

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	75 J		30 J
B		80 J	20 J
C	100 J	70 J	
D	100 J	90 J	
E		63 J	27 J
F	80 J		28 J

Which is the most energy saving fan?

How do you know?

Which is the least energy saving fan?

How do you know?

Table 5.2.2 An **e**xample of a question used in Experiment 2

When compared to the question discussed in the Experiment 1, providing all of the data as in Table 5.2.1 reduced the number of interacting elements by four, leading to eight interacting elements – still larger than Cowan's proposed limit (Cowan, 2001). Questions such as in Table 5.2.2 increased element interactivity past the twelve elements described in Experiment 1 due to the greater number of devices and the different energy relationships that needed to be considered. So, Experiment 2 provided a gradient of element interactivity across otherwise similar problem types.

In Experiment 1 an attempt had been made to assess both similar questions and questions involving transfer in the post-test. For Experiment 2, it was decided to reduce the variation in the post-test and use questions which shared the same structure but vary the context. Near transfer was still assessed but there was less far transfer when compared to Experiment 1.

A set of PowerPoint slides was created for the explicit instruction component of the experiment. These were adapted from the slides created for Experiment 1 and had reduced amounts of text.

In addition to the experimental materials, a booklet of reading materials was also prepared (see Appendix 6). These materials were of educational value and related to the topic of study (energy) but were not directly related to the experimental materials. One reading discussed the reasons why humans, unlike plants, cannot directly use sunlight as an energy resource and so it drew on concepts of photosynthesis that are unrelated to efficiency calculations. The second reading explained how some deep-sea organisms are able to make use of sulphur from deep-sea hydrothermal vents in a process similar to photosynthesis. Again, this was unrelated to efficiency calculations. These materials were used for the reading filler task described below.

5.2.1.3 Procedure

A new procedure was introduced for Experiment 2 in order to mitigate problems with the procedure used in Experiment 1.

The experiment took place in a 90-seat lecture theatre that was available for use in the learners' school. All stages of the experiment took place during the time allocated for the learners' regular science lessons. Learners were randomly assigned to one of two conditions: Problem solving – lecture (36 learners) and Lecture – problem solving (36 learners). Learners in each condition were randomly placed in alternate rows of the lecture theatre.

Instruction proceeded in three stages. In the first stage, learners in the Problem solving - lecture condition were given the booklet of problems to solve, with the following instructions: "This booklet contains some problems to try to solve. They are set in everyday situations so think how you would solve the problem in real life. You are not expected to solve all of the problems. Just do what you can." They were given 15 minutes to work on these problems. During this time, learners in the Lecture - problem solving condition completed the reading filler task. After 15 minutes, both tasks were halted and materials were collected.

In the second stage, all learners simultaneously received 10 minutes of interactive explicit instruction in the different types of energy, the principle of the conservation of energy and the canonical method for solving the light globe problems which involves calculating efficiency by dividing useful energy output by total energy input and then comparing the efficiencies of the different globes. In this stage, the PowerPoint slides were displayed on a screen to the learners. The lecture was intended to be interactive in that as the teacher performed relevant calculations, learners were also asked to perform the same calculations. The introduction of learner participation was based on summaries of teacher effectiveness research which suggest that effective explicit instruction is highly interactive (e.g. Rosenshine, 2009).

The third stage proceeded in exactly the same manner as the first stage except that the tasks were reversed between the two groups. Learners in the Lecture - problem solving condition were now given the booklet of problems to solve, whereas learners in the Problem solving - lecture condition completed the reading task.

The purpose of the reading task was purely to act as a filler activity so that the explicit instruction phase in both conditions would take place at the same time, allowing all students to receive this explicit instruction together (See Figure 5.2.1).

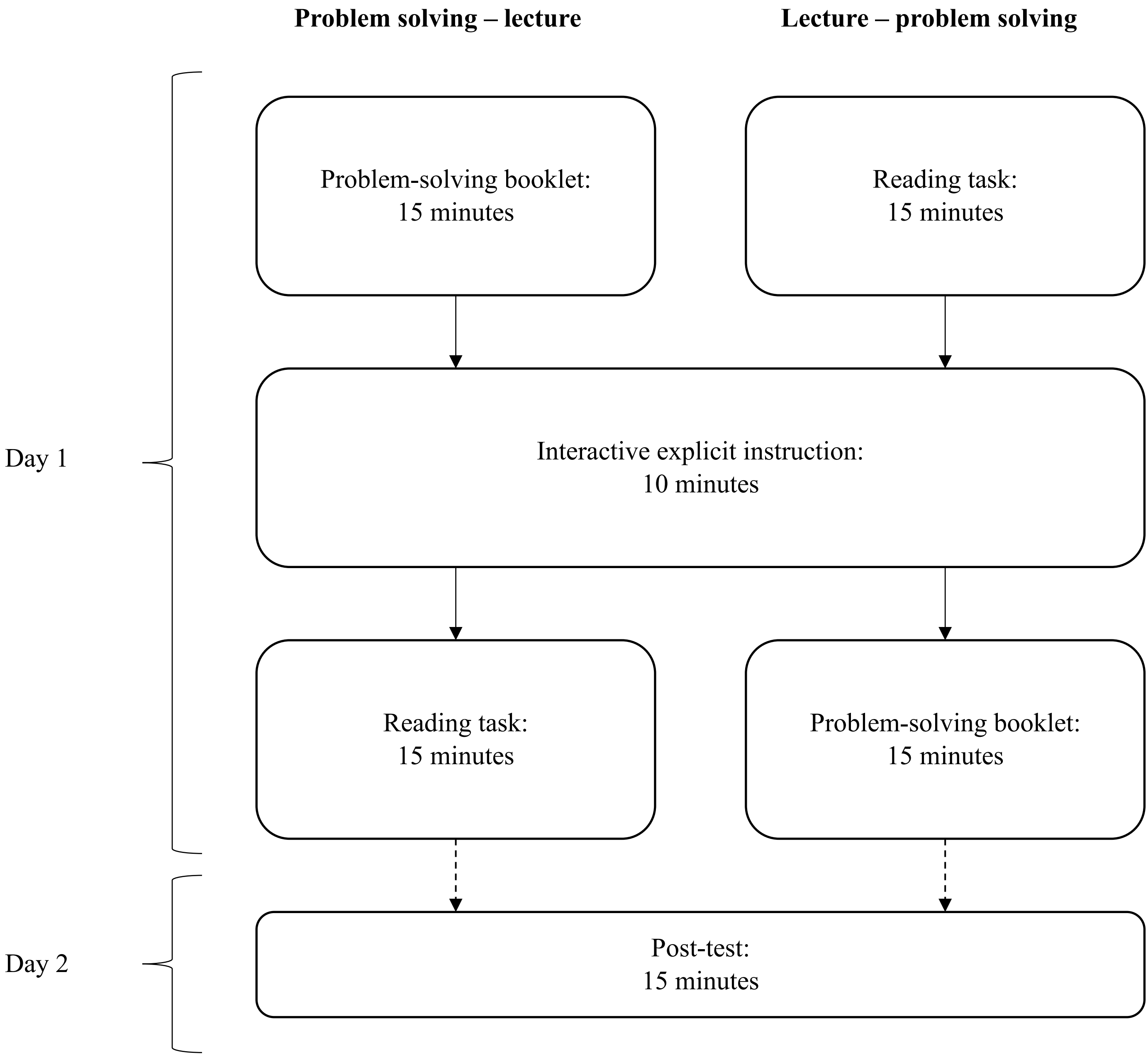

Figure 5.2.1

By structuring the experiment in this way, only strictly one experimental factor – the instructional sequence – was manipulated with all other possible influencing factors equalized between the experimental conditions. Therefore, the outcomes could be directly compared for learners who had interactive explicit instruction prior to problem solving with learners who solved problems prior to interactive explicit instruction.

One day later, learners in both conditions completed the 15-minute post-test consisting of six questions.

5.2.1.4 Scoring

A more systematic scoring system was used than in Experiment 1. Questions 1 and 6 both had two components and Questions 2-4 each had a single component, making 8 components in total. For each component, learners were required to identify a device, such as a light globe or fan, by letter and then explain why this device was the most energy saving of the options available. For each component, a mark was awarded for identifying the correct device and a mark was awarded for the explanation, making a total of 16 possible marks. If learners completed a correct efficiency calculation then this was awarded the explanation mark. Items on the post-test were moderately reliable with a Cronbach's α=.63.

Only one scorer was used to score the tests because there was no subjectivity in scoring. Either a calculated number was correct or it was not and either a selected globe letter was correct or it was not. The scorer did not have knowledge of the group to which each learner had been allocated.

5.2.2 Results

Means and standard deviations for the post-test scores are presented in Table 5.2.3. Learners in the Lecture - problem solving condition who received explicit instruction first, scored similarly to learners in the Problem solving - lecture condition who received problem-solving first, $t(70)=0.21$, $p= .83$.

	Problem solving-Lecture (*n = 36*)	*Lecture-Problem solving* (*n = 36*)
Post-test (*Total 16 marks*)	4.11 (3.50)	3.94 (3.24)

Table 5.2.3. Means and standard deviations (in brackets) for the post-test in Experiment 2.

A visual representation of the data is presented in Figure 5.2.2 (Ho, Tumkaya, Aryal, Choi, & Claridge-Chang, 2018).

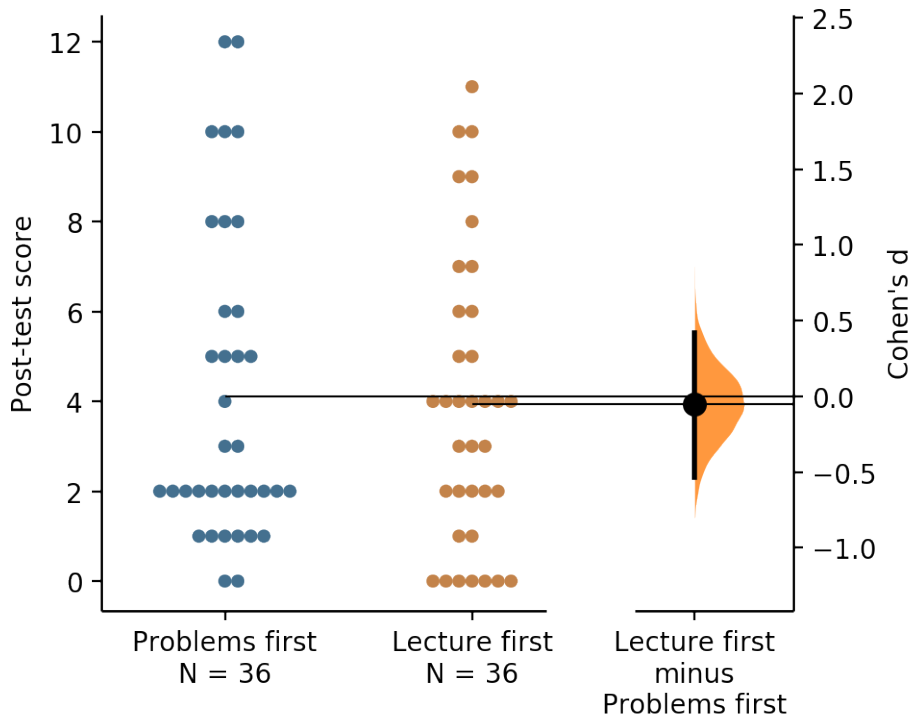

Figure 5.2.2 The Cohen's d between Problems first and Lecture first is shown in the above Gardner-Altman estimation plot for Experiment 2. Both groups are plotted on the left axes; the mean difference is plotted on a floating axis on the right as a bootstrap sampling distribution. The mean difference is depicted as a dot; the 95% confidence interval is indicated by the ends of the vertical error bar.

5.2.3 Discussion

A major flaw in the design of this experiment was that Day 1 was scheduled to take place in the final 40 minutes of a regular science lesson. After ten minutes of interactive explicit instruction, the instructor had only covered names for the different types of energy, the law of conservation of energy and a quick demonstration of calculating efficiency for a single globe. Although the intention was for students to also complete such calculations, time ran out. If it had been possible to extend the explicit instruction session, then this would not have confounded the experiment due to both conditions experiencing the same extended session. However, this was not possible because this would have reduced the time available for the third task, given the hard deadline of completing all of the tasks by the end of the lesson.

It is likely that this was the major effect influencing scores. Learners did not have an adequate demonstration of the solution method required for answering the questions and so means were low compared to the number of marks available and proportionately lower even than Experiment 1. Nevertheless, despite low scores, the increased reliability of the scores across questions indicated that the post-test was more successful at assessing a common construct.

5.3 Experiment 3

The purpose of this experiment was the same as for Experiments 1 and 2: to determine whether explicit instruction prior to problem solving was superior to problem solving prior to explicit instruction in the context of learning how to determine the efficiency of different electrical devices. The main change from Experiment 2 was a change to the experimental procedure to mitigate a number of issues identified in Experiment 2. In addition, performance on similar questions and transfer questions would be analysed separately in order to observe any differential effect.

The two competing hypotheses were identical to the previous experiments.

5.3.1 Method

5.3.1.1 Participants

The participants were 69 Year 6 students from an independent school in Victoria, Australia who had not taken part in any of the previous experiments. They were approximately 11 years old and had not previously received instruction in conservation of energy or the related concept of efficiency. An entire cohort of Year 6 students were invited to participate and all students who had returned consenting ethics approval forms and who were present on both days of the experiment were included in the sample. The students were randomly assigned to either the group that received explicit instruction first or the group that received problem solving first. Prior to the study, approval was obtained from the Human Research Ethics Advisory Panel of the University of New South Wales.

5.3.1.2 Materials

As a response to the low scores obtained in Experiment 2 that indicated that learners did not acquire the intended conceptual and procedural knowledge, it was decided to narrow the training focus to a single type of task in a consistent context – light globes. When compared to the questions used in Experiments 1 and 2, a decision was made to reduce the literacy demand. This resulted in extraneous text being stripped away. Appendix 3 provides the materials used in the presentation, problems solving task and post-test. Appendix 6 provides the materials for the reading task.

A problem solving booklet was prepared as in the previous two experiments. The problems were isomorphic and set in the same context. The only variations between questions were the different energy values and an increase in the number of globes – there were three globes in the first four questions, then five, then six in the final question. Table 5.3.1 shows an example of a question used in the problem solving booklet.

Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	80 joules	64 joules	16 joules
B	75 joules	57 joules	18 joules
C	100 joules	75 joules	25 joules

Which is the **most** energy saving light globe?

Table 5.3.1 An example of a question used in Experiment 3

As explained in Experiments 1 and 2, the question outlined in Table 5.3.1 requires the manipulation of eight elements.

The post-test was split into two components. In Component 1, all questions involved light globes and all questions presented complete data with no omissions. Essentially, Component 1 was identical to the problem solving booklet except that different energy values were used and the fourth question had four globes instead of three. The questions in Component 1 will therefore be described as ‘similar’ questions due to their similarity to the training materials.

Component 2 was designed to assess transfer and will therefore be described as ‘transfer’ questions. Variation was introduced by manipulating the contexts (e.g. fans versus globes), removing some of the data so that it needed to be computed and varying the question types – one multiple-choice question and one short answer question assessed conceptual knowledge. In the fans questions, the term ‘movement’ energy was used to avoid the need to teach students that what ‘kinetic’ energy means.

A set of PowerPoint slides were produced for use in the interactive lecture. In contrast to Experiment 3, this focused almost exclusively on the relevant problem solving procedure, with the only addition to this being a brief discussion of the names for different types of energy.

The same reading filler task was used as in Experiment 2.

5.3.1.3 Procedure

The experiment took place in a 90-seat lecture theatre that was available for use in the learners’ school. All stages of the experiment took place during the time allocated for the learners’ regular science lessons. Learners were randomly assigned to one of two conditions; Problem solving – lecture (34 learners) and Lecture – problem solving (35 learners). Learners in each condition were randomly placed in alternate rows of the lecture theatre. Each learner was issued with a basic calculator.

Instruction proceeded in three stages following the procedure outlined in Experiment 2, with the addition of a second 15 minute post-test involving transfer problems. However, in this case, the lecture phase was extended to 25 minutes in order to ensure the relevant concepts were taught. See Figure 5.3.1.

In the lecture stage, all learners simultaneously received interactive explicit instruction in the canonical method for solving the light globe problems. The lecture was interactive in that as the teacher performed relevant calculations, learners were also asked to perform the same calculations and hold their calculators aloft once they had an answer. The teacher scanned these calculator responses but did not offer any feedback to the learners. As in Experiment 2, the use of learner participation was based on summaries of teacher effectiveness research which suggest that effective explicit instruction is highly interactive (e.g. Rosenshine, 2009). However, the procedure involving holding the calculators aloft was a more formalised and potentially directly replicable implementation than in Experiment 2.

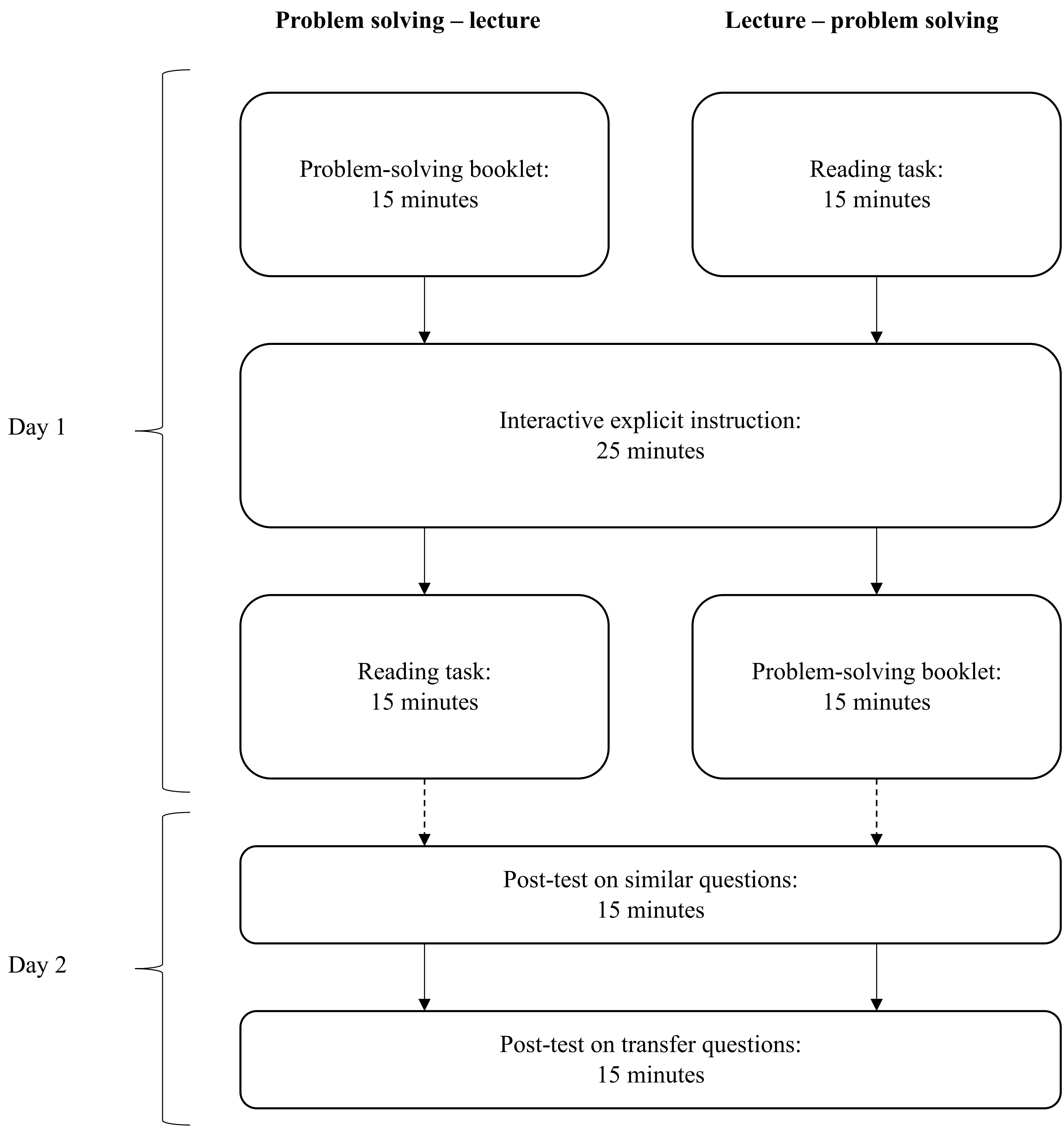
Problem solving – lecture
Lecture – problem solving
Day 1
Problem-solving booklet:
15 minutes
Reading task:
15 minutes
Interactive explicit instruction:
25 minutes
Reading task:
15 minutes
Problem-solving booklet:
15 minutes
Day 2
Post-test on similar questions:
15 minutes
Post-test on transfer questions:
15 minutes

Figure 5.3.1

As in Experiment 2, by structuring the experiment in this way, only strictly one experimental factor – the instructional sequence – was manipulated with all other possible influencing factors equalized between the experimental conditions.

One day later, learners in both conditions completed the post-test which consisted of two components. The first component included 6 similar questions and the second component consisted of 8 transfer questions. Both components were timed and lasted for 15 minutes each.

5.3.1.4 Scoring

In the similar questions, learners were required to decide which globe was the most efficient and/or which globe was the least efficient by the canonical method. In question 1, learners decided only which globe was the most efficient. In questions 2-6, learners decided which globe was the most efficient and which was the least efficient. One mark was awarded for each correctly selected globe and one mark was awarded for a calculation or correct explanation supporting each selection. The maximum possible score was 22. Items on the similar post-test component were highly reliable with Cronbach's α=.97.

In order to vary questions for the transfer component and make them more complex, the context was varied, an additional step was required to be added to the solution procedure or a non-isomeric question type was used. For questions 1, 2 and 5, which had the same structure as Component 1, the same scoring procedure was used. Questions 3 and 4 on light globes had information about the light energy given out omitted and so an additional mark was allocated to each question for calculating this missing information. Question 7 was multiple choice with a single mark allocated and question 8 was an explanation with a single mark allocated – in this case for noting the principle that energy cannot be created. The maximum possible score was 24. Items on the transfer post-test component were reliable with Cronbach's $\alpha=.82$.

Only one scorer was used to score the tests because, with the exception of Component 2, question 8, there was no subjectivity in scoring. Either a calculated number was correct or it was not and either a selected globe letter was correct or it was not. The scorer did not have knowledge of the group to which each learner had been allocated.

5.3.2 Results

Means and standard deviations for the post-test scores are presented in Table 5.3.2. Learners in the Lecture – problem solving condition who received explicit instruction first, scored similarly to learners in the Problem solving – lecture condition who received problem-solving first in both the similar problems ($t(67)= -1.72$, $p= .09$) and the transfer problems ($t(67)=-1.02$, $p=0.31$). Using a one-tailed distribution, learners in the Lecture - problem solving condition scored significantly higher than learners in the Problem solving - lecture condition $t(67)=2.41$, $p< .05$, Cohen's $d=.41$. However, it is not clear why use of a one-tailed distribution would be justified, given the contradictory predictions of the competing hypotheses.

	Problem solving-Lecture (n = 34)	*Lecture-Problem solving (n = 35)*
Similar questions (Total 22 marks)	16.35 (7.79)	19.20 (5.88)
Transfer questions (Total 24 marks)	15.12 (6.62)	16.60 (5.47)

Table 5.3.2. Means and standard deviations (in brackets) for the similar and transfer questions of Experiment 3.

A visual representation of the data for similar problems is presented in Figure 5.3.2 (Ho, Tumkaya, Aryal, Choi, & Claridge-Chang, 2018).

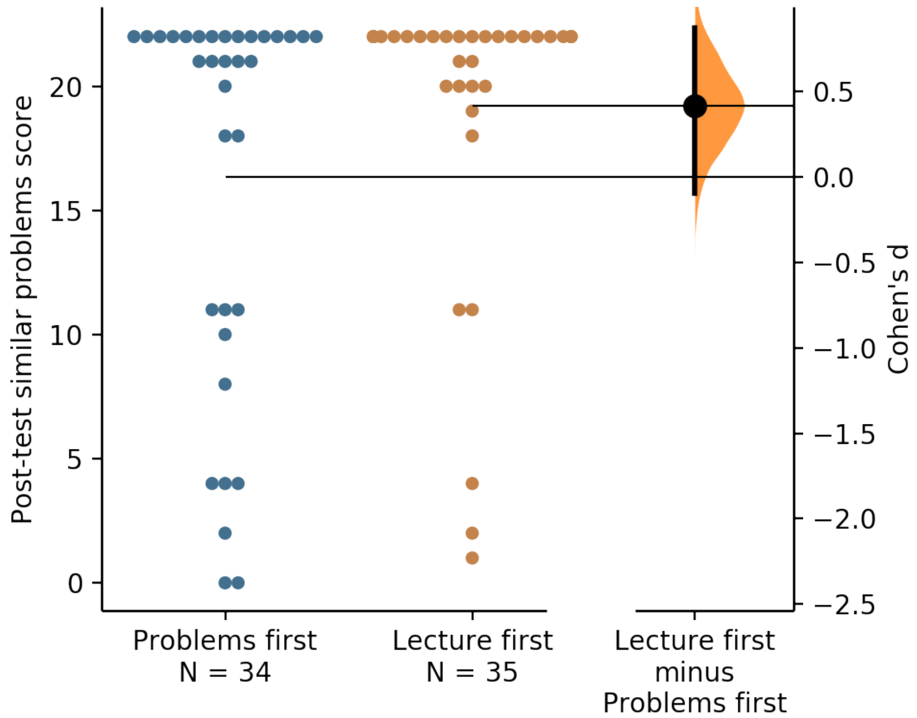

Figure 5.3.2. The Cohen's d between Problems first and Lecture first for similar problems is shown in the above Gardner-Altman estimation plot. Both groups are plotted on the left axes; the mean difference is plotted on a floating axes on the right as a bootstrap sampling distribution. The mean difference is depicted as a dot; the 95% confidence interval is indicated by the ends of the vertical error bar. (Ho et al., 2018).

A visual representation of the data for transfer problems is presented in Figure 5.3.3 (Ho, Tumkaya, Aryal, Choi, & Claridge-Chang, 2018).

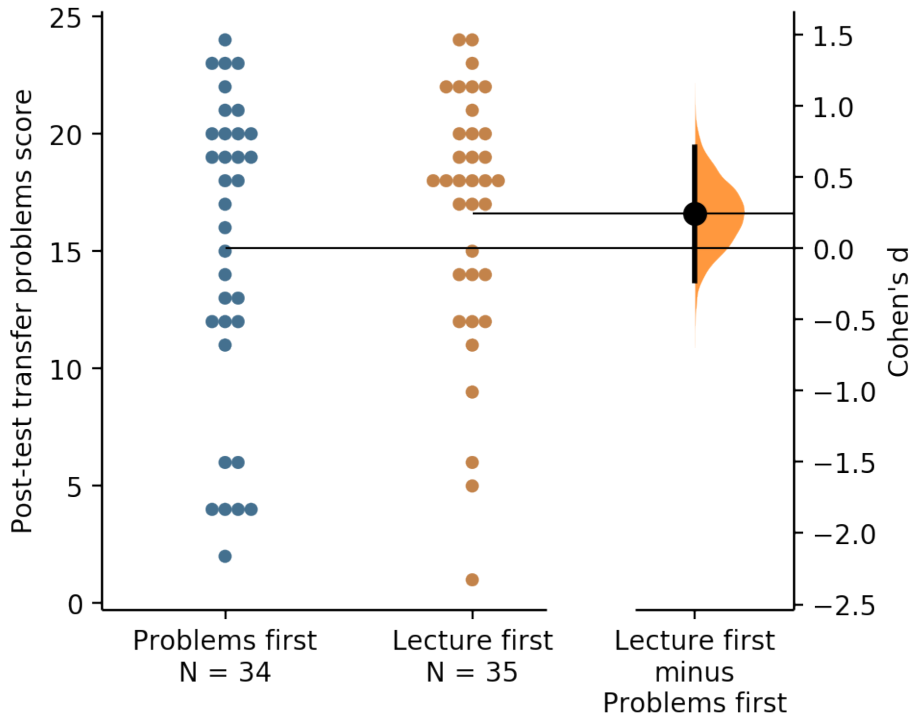

Figure 5.3.3. The Cohen's d between Problems first and Lecture first for transfer problems is shown in the above Gardner-Altman estimation plot. Both groups are plotted on the left axes; the mean difference is plotted on a floating axes on the right as a bootstrap sampling distribution. The mean difference is depicted as a dot; the 95% confidence interval is indicated by the ends of the vertical error bar. (Ho et al., 2018).

Experiment 3 offers tentative evidence of an effect favouring the lecture – problem solving condition on similar questions.

5.3.3 Discussion

Figure 5.3.2 is suggestive of the presence of a ceiling effect. After Experiment 3 had been conducted, it became apparent that flawed reasoning could lead to the correct answer to many of the questions. For instance, in questions 1, 3, 4 and 5 on the post-test, the globe with the greatest light output energy was also the most efficient and on question 6, two of the five globes had the greatest light output energy and the first to appear in the list was the most efficient. Therefore, students who used the heuristic that the higher the light energy output, the greater the efficiency, selected a globe on this basis and gave efficiency as the explanation would have scored full marks on a question despite being under a misapprehension.

At this stage, it was observed that the tasks under investigation were relatively high in element interactivity, that further hypotheses should be framed in the context of high element interactivity and that the design of further experiments should take account of element interactivity.

5.4 Experiment 4

The specific hypothesis tested in the current Experiment 4 was that explicit guidance first is superior to problem solving first using high element interactivity information. The participants received explicit instruction followed by problem solving or the same instructional episodes in the reverse sequence. An additional purpose was to resolve some of the technical issues associated with Experiment 3 in which students were able to obtain high scores by applying a misconception. This was addressed both through the design of the learning materials and the process of scoring responses.

5.4.1 Method

5.4.1.1 Participants

The participants were 71 Year 5 students from an independent school in Victoria, Australia who had not taken part in any of the previous experiments. They were approximately 10 years old and had not previously received instruction in conservation of energy or the related concept of efficiency. An entire cohort of Year 5 students were invited to participate and all students who had returned consenting ethics approval forms and who were present on both days of the experiment were included in the sample. The students were randomly assigned to either the group that received explicit instruction first or the group that received problem solving first. Prior to the study, approval was obtained from the Human Research Ethics Advisory Panel of the University of New South Wales.

5.4.1.2 Materials

Learners were asked to solve problems in which they were given data on the energy taken in per second, and the heat energy given out per second, by various light globes, as in previous experiments, and decide which globe was the most “energy saving”. Appendix 4 provides the materials used in the presentation, problems solving task and post-test. Appendix 6 provides the materials for the reading task.

The learners used a simple calculator to complete each calculation, an example of which is show in Table 5.4.1.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	80 joules	
B	150 joules	96 joules	
C	100 joules	70 joules	

Table 5.4.1. Example question data. Students were asked to determine which light globe was the most "energy saving" i.e. efficient and/or which was the least "energy saving".

To correctly solve each problem, learners needed to: subtract (1) heat given out (2) from electrical energy used (3) to obtain light energy (4) identify the input energy (5) identify the output light energy (6) divide the output light energy by the input energy (7); multiply by 100 to complete the percentage calculation for each globe from these two numbers (8) repeat for each globe (9,10,11) identify the lowest and/or highest percentages (12), resulting in twelve interacting elements, a number considerably above the current assumptions of a working memory limit of four or fewer elements when processing information (Cowan, 2001).

Various iterations of these questions were compiled into a booklet and a set of PowerPoint slides as previously. The problem-solving booklet was compiled so that there were multiple problems to complete involving increasing numbers of light globes – four questions involved three globes, one question involved five globes and one question involved six globes. In addition, the PowerPoint slides addressed a common, incorrect solution method that learners were observed to deploy in previous exploratory work – many students indicate that the globe giving out the most light energy is the most efficient. This is consistent with key design features that are typically considered to enable a Productive Failure effect (Kapur, 2016).

To avoid a problem that arose in Experiment 3, questions were audited to minimise the number of cases where incorrect reasoning – that the most energy saving globe was the one that gave out the most light energy – would lead to the identification of the correct globe.

The same reading filler task was used as in previous experiments and the post-test again consisted of two components: similar and transfer questions. For the similar questions, three questions involved three globes, two questions involved four globes, one question involved five globes and one question involved six globes. Two transfer questions involved fans where learners had to calculate the relevant movement energy, two questions involved globes, one with the irrelevant heat energy omitted and one with the electrical energy supplied omitted, requiring learners to compute this (see Table 5.4.2). The final question involved determining the truth of two statements given about two leaf blowers based upon data presented on the electrical energy used and the heat and sound energy produced by each blower.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A		65 joules	35 joules
B		64 joules	16 joules
C		57 joules	18 joules
D		70 joules	30 joules

Table 5.4.2. Example question data. Students were asked to determine which light globe was the most “energy saving” i.e. efficient and/or which was the least “energy saving”. In this case, energy used by the globe per second was omitted, requiring learners to calculate this.

5.4.1.3 Procedure

The experiment took place in a 90-seat lecture theatre that was available for use in the learners’ school. All stages of the experiment took place during the time allocated for the learners’ regular science lessons. Learners were randomly assigned to one of two conditions; Problem solving – lecture (35 learners) and Lecture – problem solving (36 learners). Learners in each condition were randomly placed in alternate rows of the lecture theatre. Each learner was issued with a basic calculator.

Instruction proceeded in the same way as Experiment 3 (see Figure 5.3.1). The two-component post-test was completed the following day.

5.4.1.4 Scoring

Scoring was altered from Experiment 3 in order to ensure learners did not gain full marks for using flawed reasoning.

In the similar questions, learners were required to decide which globe was the most efficient and/or which globe was the least efficient by the canonical method. In order to do this, learners first needed to calculate the light energy given out by each globe. A total of one mark was awarded for obtaining *all* of the correct values for the light energy given out. If a single value was incorrect then this mark was not awarded. Learners then needed to calculate the efficiency of each globe separately. Each of these multiple calculations was scored as 1 if correct. Finally, the correct decisions of the most efficient globes (letter choice/s) were also scored as 1. The maximum possible score was 48. It was possible for learners to guess the correct letter choice but in this case, they would not have the supporting multiple calculations and so would not score fully for the question. Items on the similar post-test component were highly reliable with Cronbach's α=.96.

In order to vary questions for the transfer component and make them more complex, usually an additional step was required to be added to the solution procedure. The transfer questions were scored similarly, with correct calculations and correct answers each being scored with 1 mark. The maximum possible score was 27. Items on the transfer post-test component were highly reliable with Cronbach's α=.88.

Only one scorer was used to score the tests because there was no subjectivity in scoring. Either a calculated number was correct or it was not and either a selected globe letter was correct or it was not. The scorer did not have knowledge of the group to which each learner had been allocated.

5.4.2 Results

Means and standard deviations for the post-test scores are presented in Table 5.4.3. For the similar post-test questions, learners in the Lecture - problem solving condition who received explicit instruction first, scored significantly higher than learners in the Problem solving - lecture condition who received problem-solving first, $t(69)=2.41$, $p= .02$, Cohen's $d=.57$.

	Problem solving-Lecture *(n = 35)*	*Lecture-Problem solving* *(n = 36)*
Similar questions *(Total 48 marks)*	21.40 (15.90)	31.06 (17.79)
Transfer questions *(Total 27 marks)*	10.20 (8.87)	15.22 (9.15)

Table 5.4.3. Means and standard deviations (in brackets) for the similar and transfer questions of Experiment 4.

A visual representation of the data is presented in Figure 5.4.1 (Ho, Tumkaya, Aryal, Choi, & Claridge-Chang, 2018).

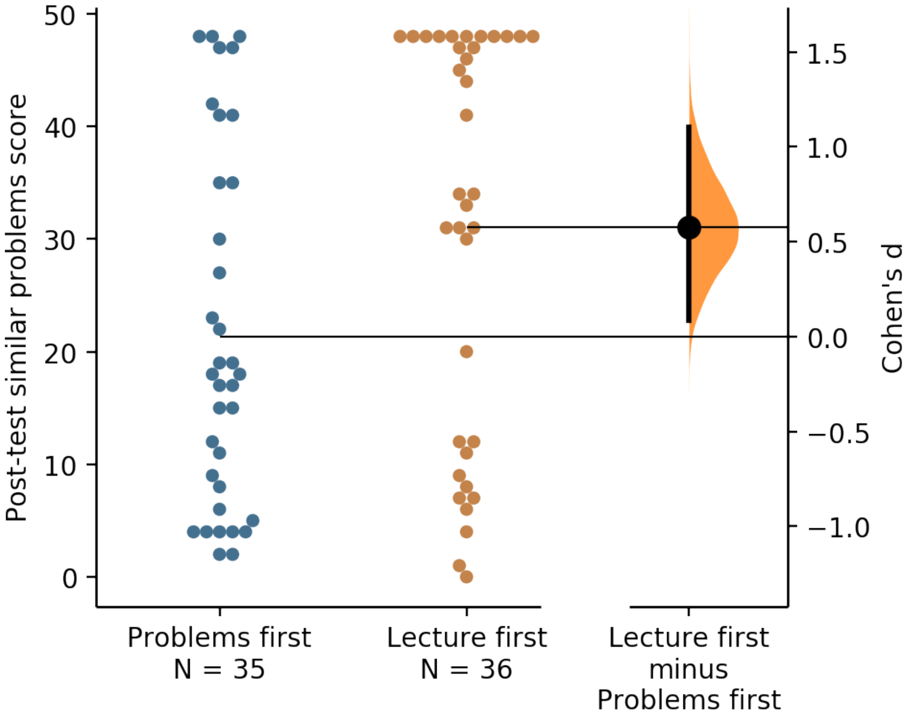

Figure 5.4.1. The Cohen's d between Problems first and Lecture first for similar problems is shown in the above Gardner-Altman estimation plot. Both groups are plotted on the left axes; the mean difference is plotted on a floating axes on the right as a bootstrap sampling distribution. The mean difference is depicted as a dot; the 95% confidence interval is indicated by the ends of the vertical error bar. (Ho et al., 2018).

Similarly, learners in the Lecture – problem-solving condition who received explicit instruction first, scored significantly higher on transfer questions than learners in the Problem-solving – lecture condition who received problem-solving first, $t(69)=2.35$, $p= .02$, Cohen' s $d=.56$. A visual representation of the data is presented in Figure 5.4.2 (Ho et al., 2018).

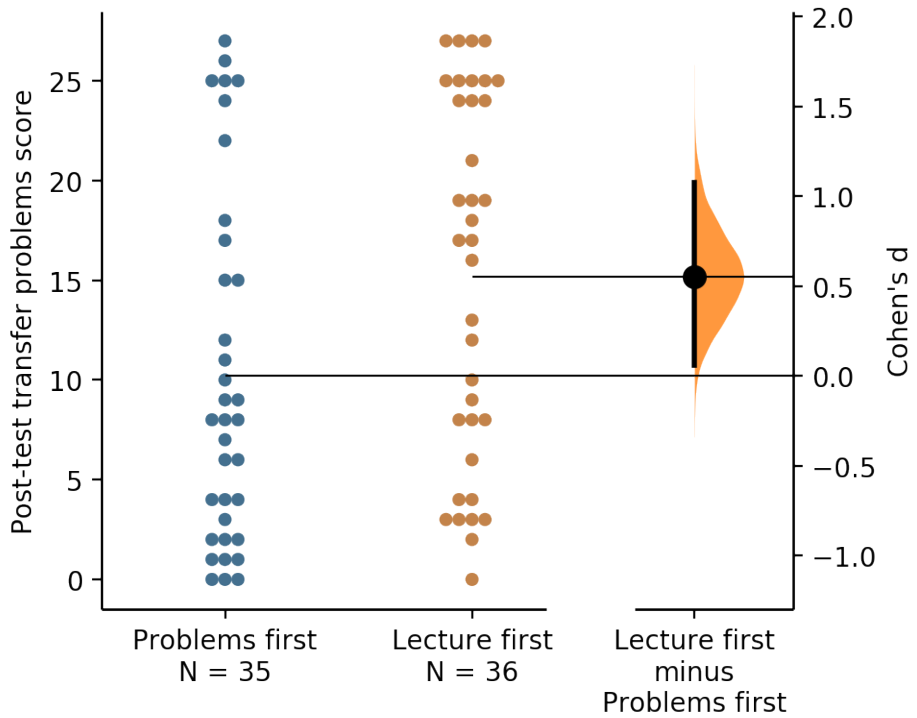

Figure 5.4.2. The Cohen's d between Problems first and Lecture first is shown in the above Gardner-Altman estimation plot. Both groups are plotted on the left axes; the mean difference is plotted on a floating axes on the right as a bootstrap sampling distribution. The mean difference is depicted as a dot; the 95% confidence interval is indicated by the ends of the vertical error bar (Ho et al., 2018).

5.4.3 Discussion

These results strongly support the Lecture – problem-solving sequence. Mean test scores for both the similar and transfer problems were almost 50% higher using the Lecture – problem-solving sequence compared to the Problem-solving – lecture sequence.

As expected for high element interactivity information, Experiment 4 did not lead to a superiority of the Problem solving – lecture sequence. Instead there is evidence that the Lecture – problem solving sequence resulted in higher test scores.

5.5 Experiment 5

The purpose of this experiment was to investigate the hypothesis that a Productive Failure effect would still not be observed with problems that had high element interactivity, but not as high as in Experiment 4, and that learners would therefore learn more from explicit instruction followed by problem solving. The participants received explicit instruction followed by problem solving or the same instructional episodes in the reverse sequence.

5.5.1 Method

5.5.1.1 Participants

The participants were 64 Year 5 students from an independent school in Victoria, Australia who had not taken part in any of the previous experiments. They were approximately 10 years old and had not previously received instruction in conservation of energy or the related concept of energy efficiency. An entire cohort of Year 5 students were invited to participate and all students who had returned consenting ethics approval forms and who were present on both days of the experiment were included in the sample. The students were randomly assigned to either the group that received explicit instruction first or the group that received problem solving first. Prior to the study, approval was obtained from the Human Research Ethics Advisory Panel of the University of New South Wales.

5.5.1.2 Materials

Materials were similar to Experiment 4, with the key difference being that the useful light energy given out was presented to learners rather than learners being required to compute these values (see Figure 5.5.1).

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	30 joules	15 joules
B	20 joules	12 joules
C	30 joules	12 joules

Table 5.5.1. Example question data. Students were asked to determine which light globe was the most “energy saving” i.e. efficient and/or which was the least “energy saving”.

As previously discussed, items such as that shown in Table 5.5.1 consist of eight interacting elements for relatively novice learners.

Various iterations of these questions were compiled into a booklet and a set of PowerPoint slides, with the latter to be used in the interactive explicit instruction phase of the experiment. The problem-solving booklet was compiled so that there were multiple problems to complete involving increasing numbers of light globes – four questions involved three globes, one question involved five globes and one question involved six globes. Again, the PowerPoint slides addressed the common, incorrect solution method that the globe giving out the most light energy is the most efficient.

The reading task was identical to previous experiments.

For the post-test, two sets of questions were prepared as in Experiments 3 and 4. The similar questions used the same context of light globes but the values used in the questions were different (three questions involves three globes and then one question each involved four, five and six globes).

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Fan	Electrical energy used by the fan per second	Movement energy given out per second
A	30 joules	15 joules
B	20 joules	12 joules
C	30 joules	12 joules

Table 5.5.2. Example of a transfer question. Students were asked to determine which fan was the most "energy saving" i.e. efficient and/or which was the least "energy saving".

Again, questions were audited to minimise the number of cases where incorrect reasoning – that the most energy saving globe was the one that gave out the most light energy – would lead to the identification of the correct globe.

For the transfer component, two questions were set in the different context of an electric fan (see Table 5.5.2). Two questions involved light globes but presented additional redundant information in the table about the heat energy given out by these globes, requiring learners to select the useful energy. A final question required learners to use the principle of conservation of energy to complete an additional step and compute the light energy given out when given data on the electrical energy used and heat energy given out (see Table 5.5.3). This was essentially the same as the main task that students completed in Experiment 4.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	50 joules	25 joules	
B	60 joules	30 joules	
C	50 joules	24 joules	
D	60 joules	33 joules	

Table 5.5.3. Example of a transfer question. Students were asked to determine which light globe was the most efficient and/or which was the least efficient. Appendix 5 provides the materials used in the presentation, problems solving task and post-test. Appendix 6 provides the materials for the reading task.

5.5.1.3 Procedure

The experiment took place in a 200-seat lecture theatre that was available for use in the learners' school. All stages of the experiment took place during the time allocated for the learners' regular science lessons. Learners were randomly assigned to one of two conditions; Problem solving – lecture (30 learners) and Lecture – problem solving (34 learners). The difference in the group sizes was due to the fact that some students were required to withdraw to participate in a sporting event post randomisation and this had a differential impact on the conditions. Learners in each condition were randomly placed in alternate rows of the lecture theatre. Each learner was issued with a basic calculator.

Instruction proceeded in the same way as Experiments 3 and 4 (see Figure 5.3.1). The two-component post-test was completed six days later.

It is important to note that the different delay between instruction and post-test between Experiments 4 and 5 (1 day versus 6 days) was not an intentional manipulation. It arose from the practicalities of when regular science classes were scheduled for these learners and when the experimental sequence of teaching would fit in with the rest of the learners' curriculum. Nevertheless, it is an important difference when analysing the results of the two experiments.

5.5.1.4 Scoring

In the similar questions, learners were required to decide which globe was the most efficient and/or which globe was the least efficient by the canonical method. In order to do this, learners needed to calculate the efficiency of each globe separately. Each of these multiple calculations was therefore scored as 1 if correct and the correct decisions of the most efficient globes (letter choice/s) were also scored as 1. The maximum possible score was 35. It was possible for learners to guess the correct letter choice but in this case, they would not have the supporting multiple calculations and so would not score fully for the question. Items on the similar post-test component were highly reliable with Cronbach's α=.94.

In order to vary questions for the transfer component and make them more complex, usually an additional step was required to be added to the solution procedure. The transfer questions were scored similarly, with correct calculations and correct answers each being scored with 1 mark. The maximum possible score was 28. Items on the transfer post-test component were reliable with Cronbach's α=.75.

Only one scorer was used to score the tests because there was no subjectivity in scoring. Either a calculated number was correct or it was not and either a selected globe letter was correct or it was not. The scorer did not have knowledge of the group to which each learner had been allocated.

5.5.2 Results

Means and standard deviations for the post-test scores are presented in Table 5.5.4. For the similar post-test questions, learners in the Lecture - problem solving condition who received explicit instruction first, scored significantly higher than learners in the Problem solving - lecture condition who received problem-solving first, $t(62)=2.25$, $p= .03$, Cohen's $d=.56$.

	Problem solving-Lecture (n = 30)	*Lecture-Problem solving (n = 34)*
Similar questions (Total 35 marks)	17.57 (12.39)	24.68 (12.78)
Transfer questions (Total 28 marks)	8.33 (7.60)	11.41 (5.33)

Table 5.5.4. Means and standard deviations (in brackets) for the similar and transfer questions of Experiment 5.

A visual representation of the data is presented in Figure 5.5.1 (Ho, Tumkaya, Aryal, Choi, & Claridge-Chang, 2018).

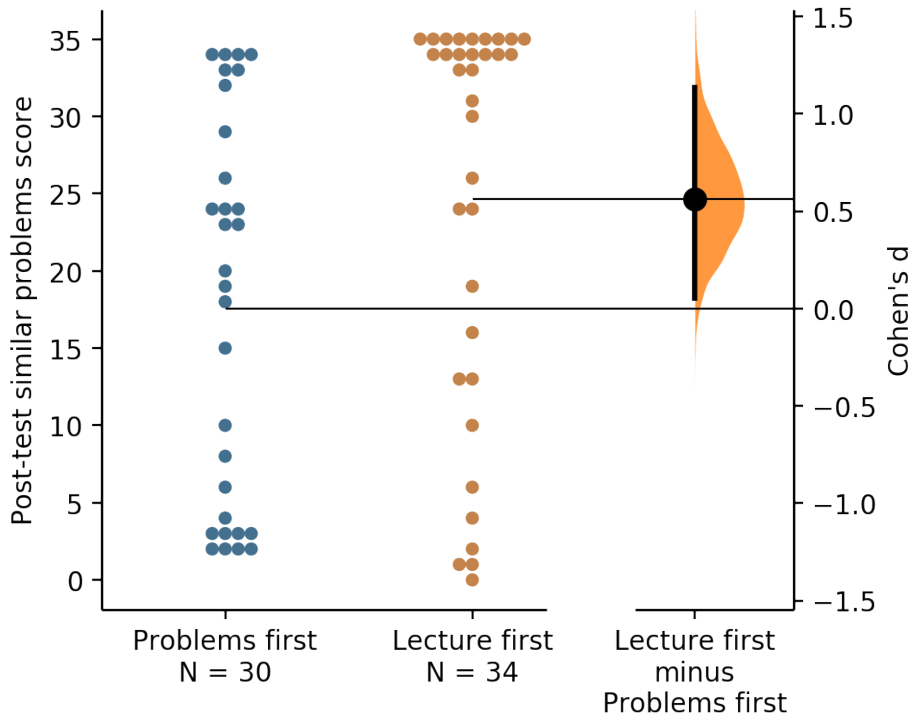

Figure 5.5.1. The Cohen's d between Problems first and Lecture first is shown in the above Gardner-Altman estimation plot. Both groups are plotted on the left axes; the mean difference is plotted on a floating axes on the right as a bootstrap sampling distribution. The mean difference is depicted as a dot; the 95% confidence interval is indicated by the ends of the vertical error bar (Ho et al., 2018).

For the transfer post-test questions, there was no significant difference between the conditions, $t(62)=1.89$, $p=.06$, Cohen's $d=.47$. A visual representation of the data is presented in Figure 5.5.2 (Ho et al., 2018).

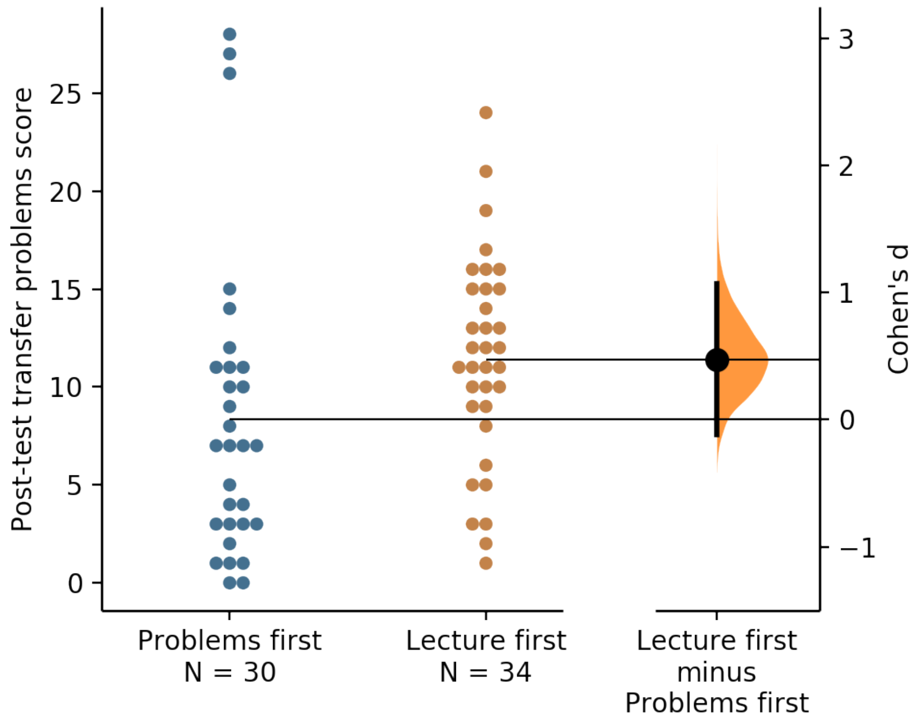

Figure 5.5.2. The Cohen's d between Problems first and Lecture first is shown in the above Gardner-Altman estimation plot. Both groups are plotted on the left axes; the mean difference is plotted on a floating axes on the right as a bootstrap sampling distribution. The mean difference is depicted as a dot; the 95% confidence interval is indicated by the ends of the vertical error bar (Ho et al., 2018).

5.5.3 Discussion

As in Experiment 4, these results support the Lecture – problem-solving sequence. The effect on similar questions was similar to Experiment 4 but the effect on transfer questions was not significant. This could be due to the reduction in element interactivity between Experiments 4 and 5 or that the qualitatively different, higher element interactivity training task from Experiment 4 was suited to greater transfer. It also could be due to the difference in the timing of the post-test, with an effect that is apparent after one day washing out after six days.

A Productive Failure effect was not observed for either post-test component, consistent with the original hypothesis. Explicit instruction prior to problem solving led to more learning as measured by the similar questions post-test but not the transfer questions post-test, partially validating the hypothesis.

Chapter 6
General discussion

A series of five experiments was conducted to test the competing predictions of Productive Failure and Cognitive Load Theory. Drawing upon human cognitive architecture, Cognitive Load Theory predicts that for novices learning relatively complex problem-solving techniques, explicit teaching prior to problem solving is beneficial when compared to the reverse order. This is because it is assumed that this sequence will prevent learners' working memories from becoming overloaded. In contrast, Productive Failure predicts that problem solving prior to explicit teaching would be more effective. For instance, the problem-solving episode may highlight knowledge gaps, increase awareness of the deep structure of a problem type or increase motivation.

The first three experiments did not provide strong evidence for the superiority of either order due to a series of factors unrelated to the hypotheses. Following refinement, including the introduction of a novel experimental procedure designed to eliminate a key confound, Experiments 4 and 5 provided strong evidence that explicit instruction prior to problem solving is the superior sequence in this context.

This conclusion is relevant only to information that is relatively high in element interactivity such as the information used in the experiments. However, previous experiments that have found a Productive Failure effect have used contexts that appear to have similarly high levels of element interactivity. This may be due to differences in experimental design or because the Productive Failure effect is highly sensitive to context. It may also be due to element interactivity being reduced in these studies due to the learners involved already possessing relevant expertise (Chen, Kalyuga, & Sweller, 2017).

6.1 Human Cognitive Architecture

Drawing on the distinction made by David C. Geary (1995), Cognitive Load Theory assumes two classes of knowledge that humans may acquire – biologically primary knowledge and biologically secondary knowledge. Biologically primary knowledge is knowledge we have evolved to acquire. It has been advantageous for individuals to acquire this knowledge over evolutionarily significant timescales and so the process of evolution by natural selection has equipped humans with the ability to acquire this knowledge without conscious effort or innately. Examples of biologically primary knowledge include knowledge of an individual's native tongue and 'folk biology' – knowledge of what food can be eaten and where it can be found.

In contrast, biologically secondary knowledge is the result of more recent cultural innovations such as the advent, a few thousand years ago, of written language (Postgate, 1992; Norman, 1988; Marcus, 1980). Even if possession of such knowledge gives an individual an advantage in the process of natural selection – a proposition that is not obvious and should not be assumed – there has been insufficient time for humans to generate and select the genetic mutations needed to evolve the capacity to acquire this knowledge innately.

Cognitive Load Theory assumes a model of the mind as a natural information processing system analogous to the way that evolution by natural selection processes information (Sweller & Sweller, 2006; Sweller, Ayres, & Kalgyuga, 2011). There are two ways that biologically secondary knowledge may be acquired – by borrowing and reorganising knowledge possessed by another individual and by randomly generating new knowledge and testing it for efficacy. Both processes take place in working memory, a system that is highly constrained and that can process only a few items at a time. In part, these constraints arise from the vast number of ways that new knowledge may be combined and ordered. For instance, four items may be arranged in $4 \times 3 \times 2 \times 1 = 24$ ways, whereas six items may be arranged $6 \times 5 \times 4 \times 3 \times 2 \times 1 = 720$ ways.

Once processed by working memory, knowledge can pass into an effectively unconstrained long-term memory. Knowledge is assumed to be organised in long-term memory in 'schemas' – networks of concepts arranged by their semantic relationships (Sweller, Ayres, & Kalyuga, 2011; Seel, 2012). Such knowledge, when organised, removes the problem of the vast number of ways knowledge items can be arranged and so this knowledge can be drawn upon effortlessly by working memory to complete tasks or task components (Sweller, Ayres, & Kalyuga, 2011), expanding the number of operations working memory can perform.

Evolution by natural selection requires no central processor to guide it. In an analogous fashion and contrary to many computer-inspired models of human cognitive architecture (see e.g. Baddeley and Hitch, 1974), the model of human cognitive architecture assumed by Cognitive Load Theory requires no central executive and, instead, direction is provided by schemas held in long-term memory (Sweller, Ayres, & Kalgyuga, 2011) interacting with the external environment. The acquisition of knowledge in long-term memory therefore changes who humans are and what they can do.

6.2 Cognitive Load Theory

By assuming the natural information processing model described above, Cognitive Load Theory seeks to describe the relationship between the cognitive load imposed by different instructional procedures and the acquisition of biologically secondary knowledge in long-term memory (Sweller, Van Merriënboer, & Paas, 2019), with a view to generating novel instructional designs that are effective for the acquisition of biologically secondary knowledge.

A key feature of this cognitive architecture – one that is widely accepted in the field of psychology – is the fact that working memory is highly constrained and may process only up to about four new items at a time (Cowan, 2001). Within Cognitive Load Theory, such constraints are assumed to not apply to biologically primary knowledge or to knowledge already organised in long-term memory.

Due to constraints on working memory, Cognitive Load Theory predicts that load imposed upon working memory by stimuli extraneous to a learning task, such as an irrelevant illustration, should be minimised, at least for novices. Such load is termed 'extraneous load'. In contrast, the load intrinsic to completing the learning task – the 'intrinsic load' – should be optimised. In other words, it should not be reduced to zero but should be kept within the four-item or less limit of working memory. For some tasks, this implies breaking a larger task down into smaller components and training these components individually before bringing them back together (see e.g. Martin, 2016).

Many learning contexts contain items that are connected. For instance, in the equation $3x = 18$, the items, $3, x, =$ and 18 have a relationship with each other. If we manipulate one item, it affects the others. These relationships represent additional items or 'elements' to be processed by novice learners. In this case, the context is high in 'element interactivity'. Such a context may be contrasted with one such as learning the symbols of the elements of the periodic table in chemistry. In this second case, although a challenging task, each symbol is independent of every other symbol and so they may be learnt in isolation – the symbols do not interact. Therefore, this is a case of low element interactivity (Chen, Kalyuga, & Sweller, 2017). Alternatively, another way of obtaining low element interactivity is to involve more expert learners who already have relevant schemas in long-term memory and thus who do not have to process all the elements and their relationships as separate items in working memory. Different instructional procedures may be optimal for high and low element interactivity contexts with the need to reduce intrinsic load to within the four-item limit more acute for high element interactivity contexts (Chen, Kalyuga, & Sweller, 2015).

Fully randomised controlled trials, as well as quasi-experimental trials, conducted in the field of Cognitive Load Theory have established a number of ‘effects’ where some instructional procedures are found to be superior to others (Sweller, Van Merriënboer, & Paas, 2019). The foundational effect is the ‘worked example effect’ where studying worked examples leads to more learning for novices than attempting to solve equivalent problems (Sweller & Cooper, 1985).

Problem solving imposes a particularly high load on working memory because there are so many possible combinations of moves and due to the process whereby each move must be evaluated in terms of whether it represents progress towards the goal state – a process known as ‘means-ends analysis’ (Tricot & Sweller, 2014). By providing learners with a worked example, we guide their attention to specific moves in an organised sequence, reducing the number of items it is necessary to simultaneously process.

Other effects add to this finding. For instance, the problem completion effect involves asking learners to study a worked example but complete one of the steps, such as the last step, for themselves. Such an approach can raise intrinsic load if it falls too low, either because the task is inherently low in element interactivity or because element interactivity has been reduced as learners have begun to gain relevant problem-solving schemas. The problem completion effect is therefore compatible with the ‘generation effect’ where learners benefit from generating their own answers in low element interactivity contexts such as learning lists of paired words (Slamecka & Graf, 1978; Hirschman & Bjork, 1988; Schwarz, Lindgren, & Lewis, 2009).

Therefore, Cognitive Load Theory predicts that when element interactivity is relatively high, as it is in the empirical studies described above, asking novice learners to solve problems would overload working memory and would therefore not be beneficial.

6.3 Productive Failure

In contrast to Cognitive Load Theory, the theory of Productive Failure suggests there are benefits to open-ended problem solving if it is followed by explicit instruction (Kapur, 2008). These benefits may be due to a problem-solving phase activating prior knowledge, increasing learners' awareness of their own knowledge gaps, increasing awareness of the deep structure of a problem type and increasing motivation (see e.g. Russo & Hopkins, 2019; Nachtigall, Serova, & Rummel, 2020).

Such benefits conflict with the predictions of Cognitive Load Theory in instances when element interactivity is high. Nevertheless, instructional designs incorporating Productive Failure, or similar approaches where a problem-solving phase precedes explicit instruction, often make use of relatively high element interactivity contexts such as asking learners to compute standard deviation or investigate the concept of density (e.g Schwartz & Martin, 2004; Kapur, 2012).

One difficulty that arises in attempts to investigate the potential for Productive Failure is that of experimental design. A straightforward comparison of the two phases of Productive Failure – problem-solving followed by explicit instruction – with explicit instruction alone, varies more than one factor at a time. A potential solution is to have two conditions that each include the two problem-solving and explicit instruction phases, but that switch the order of these phases between conditions. One condition would therefore consist of problem-solving followed by explicit instruction and the other would consist of explicit instruction followed by problem-solving.

A number of experiments have found evidence to support the efficacy of Productive Failure (e.g. Schwartz & Bransford, 1998; Schwartz & Martin, 2004; DeCaro & Rittle-Johnson, 2012; Schwartz, Chase, Oppezzo, & Chin, 2011; Kapur, 2012; Kapur 2014; Loibl & Rummel 2014a, 2014b; Jacobsen, Markauskaite, Portolese, Kapur, Lai, & Roberts, 2017; Lai, Portolese, & Jacobson, 2017; Weaver, Chastain, DeCaro, & DeCaro, 2018; Halmo, Sensibaugh, Reinhart, Stogniy, Fiorella, & Lemons, 2020) but only a subset of these have varied the order of the two phases between conditions while varying nothing else (Loibl & Rummel, 2014b; Kapur 2014; Lai et al., 2017; DeCaro & Rittle-Johnson, 2012; Weaver, Chastain, DeCaro, & DeCaro, 2018). One such study (Kapur, 2014) asked students in the explicit instruction – problem-solving condition to solve a problem in as many ways as they could, *after* being shown the canonical solution; a procedure with questionable ecological validity because it seems unlikely that teachers would choose such an approach in regular classrooms.

Some controlled studies that switch the order of explicit instruction and problem-solving find a positive effect of Productive Failure on conceptual knowledge but a null or negative effect on procedural knowledge (e.g. DeCaro and Rittle-Johnson, 2012). However, conceptual knowledge is not well defined, and tests of conceptual knowledge may effectively be tests of simple, declarative knowledge, such as a definition of the equals sign in an equation (Crooks & Alibali, 2014). Declarative knowledge of this kind is low in element interactivity and such findings are therefore potentially consistent with Cognitive Load Theory.

Several studies contradict the predictions of Productive Failure. For instance, experiments have been conducted where learners study worked examples – a form of explicit instruction – and solve relevant problems, with the order of these two instructional phases being reversed between the control and experimental groups. Such experiments tend to demonstrate the advantages of studying worked examples prior to problem-solving over the reverse order

(Van Gog, Kester, & Paas, 2011; Leppink, Paas, Van Gog, Van der Vleuten, & Van Merrienboer, 2014; Hsu, Kalyuga, & Sweller, 2015).

6.4 Conflicting predictions.

A conflict therefore arises between the predictions of Cognitive Load Theory and of Productive Failure.

For learning tasks that are low in element interactivity, either because they are intrinsically isolated tasks, such as learning a particular piece of terminology, or because the learners already possess substantial and relevant domain expertise, Cognitive Load Theory is consistent with the prediction of Productive Failure that an exploration phase prior to instruction would be beneficial. However, for learning tasks that are relatively high in element interactivity, including tasks that are frequently the subject of Productive Failure research such as computing standard deviation, Cognitive Load Theory suggests that explicit instruction prior to problem solving would be optimal for novice learners whereas Productive Failure predicts the opposite sequence would be superior.

Furthermore, an opportunity arose to conduct randomised controlled trials that vary only one factor at a time, and which would add to the literature on Productive Failure.

6.5 Selection of context

Productive Failure research has been conducted in several different domains and has included learning tasks involving concepts such as density and standard deviation. It was decided to extend previous work by selecting a distinct physics concept high in element interactivity and with similarities to concepts addressed in previous Productive Failure research. The context chosen was the energy efficiency of light globes.

Efficiency calculations of this kind afford the opportunity to be consistent with a set of design features described by Kapur (2016) that allow for the proposed benefits of a Productive

Failure approach. The attempt to determine which is the most ‘energy saving’ globe can be tackled intuitively and activates prior formal and intuitive knowledge. This means learners can attempt to solve the problem without instruction. This contrasts with a case where, for example, learners do not understand the question or cannot interpret the vocabulary used. The term ‘efficiency’ is absent from the question for this reason. Moreover, a common incorrect solution method is to choose the globe with the highest useful energy output. This can then be built upon and corrected in the instructional phase, as Kapur (2016) suggests, allowing a comparison of the incorrect learner-developed solution method with the canonical method.

This context also has intrinsic value that involves mathematical concepts such as proportion. It has a wider resonance in the current geopolitical environment where efforts are being made to avert dangerous levels of climate change by considering questions of energy consumption and efficiency. To adequately tackle this issue, we will need a supply of future engineers who understand the relevant concepts.

The empirical studies were intended to investigate the effect of the order of activities on learning. Specifically, each experiment compared the effect of a Problem solving – lecture condition with a Lecture – problem solving condition.

In the initial stages of the empirical studies, a wide range of related concepts were addressed. As it became clear that addressing these concepts within the confines of a limited study was impractical, it was decided to narrow the focus to calculations of energy efficiency alone.

Mindful of previous findings that found differential effects for conceptual and procedural knowledge (e.g. DeCaro and Rittle-Johnson, 2012), learners were assessed both on their ability to complete tasks similar to the training tasks and on near-transfer tasks. Near transfer tasks were chosen as a proxy for conceptual knowledge rather than a direct assessment of conceptual knowledge due to the difficulties with the latter highlighted by Crooks and Alibali (2014).

6.6 Hypotheses

Initial hypotheses did not consider the impact of element interactivity. Once the relevance of element interactivity became apparent, two main hypotheses were developed that applied in the context of the relatively high element interactivity, for novice learners, of the energy efficiency learning tasks:

- H1: There would be a Productive Failure effect where learners would learn more from problem solving prior to explicit instruction
- H2: Problem solving prior to explicit instruction would overwhelm working memory and learners would learn more from explicit instruction prior to problem solving

6.7 Empirical studies

Five fully randomised experiments were conducted with students in Australian Years 5 and 6 who were approximately 10-11 years of age. These learners had no previous instruction in energy, the law of conservation of energy or efficiency. The first three experiments refined the experimental method, with the final two experiments generating substantive results.

6.7.1 Experiment 1

For Experiment 1, a five minute and 32 second video and a problem-solving booklet were prepared. The video contained a silent PowerPoint presentation that defined relevant terms and instructed learners in the law of conservation of energy and efficiency calculations. The problem-solving booklet required learners to solve problems involving efficiency calculations. Element interactivity varied across problems and was relatively high, with some requiring the processing of around twelve interacting elements.

48 Year 6 students were randomly allocated to two groups. The Problem solving – lecture group (26 learners) attempted the problem-solving booklet for ten minutes prior to watching the video on a laptop computer. The Lecture – problem solving group (22 learners) watched the video prior to completing the problem-solving booklet for ten minutes. The treatment component of the study took place during a regular science lesson.

Three days after the treatment component, learners took a post-test, again in their regular science lesson. The difference in the number assigned to each group reflects that some students initially assigned to one of the two groups had a music lesson on the day of either the treatment or the post-test and so could not participate. This differentially affected students in the Lecture – problem solving group.

Results from Experiment 1 were inconclusive, demonstrating no statistically significant difference between the two conditions. Moreover, several issues stemmed from the design of the experiment. Firstly, the two conditions were assigned to different classrooms and teachers. The teachers in these classrooms treated the task differently. One teacher followed the script supplied by the researcher, whereas the other teacher expanded upon this script at some length.

Results demonstrated that few learners in either condition achieved the targeted learning, gaining means of 9.15 and 8.27 out of a possible 23. The video was brief and targeted several objectives in addition to those required to conduct efficiency calculations. The post-test also assessed some of these other aims, leading to a low Cronbach's α value of .41. In addition, the video was not interactive and so was not in line with prior research on effective forms of explicit instruction (see e.g. Rosenshine, 2012).

It was therefore decided to significantly alter the experimental procedure for Experiment 2.

6.7.2 Experiment 2

For Experiment 2, a novel design was employed as shown in Figure 6.7.1

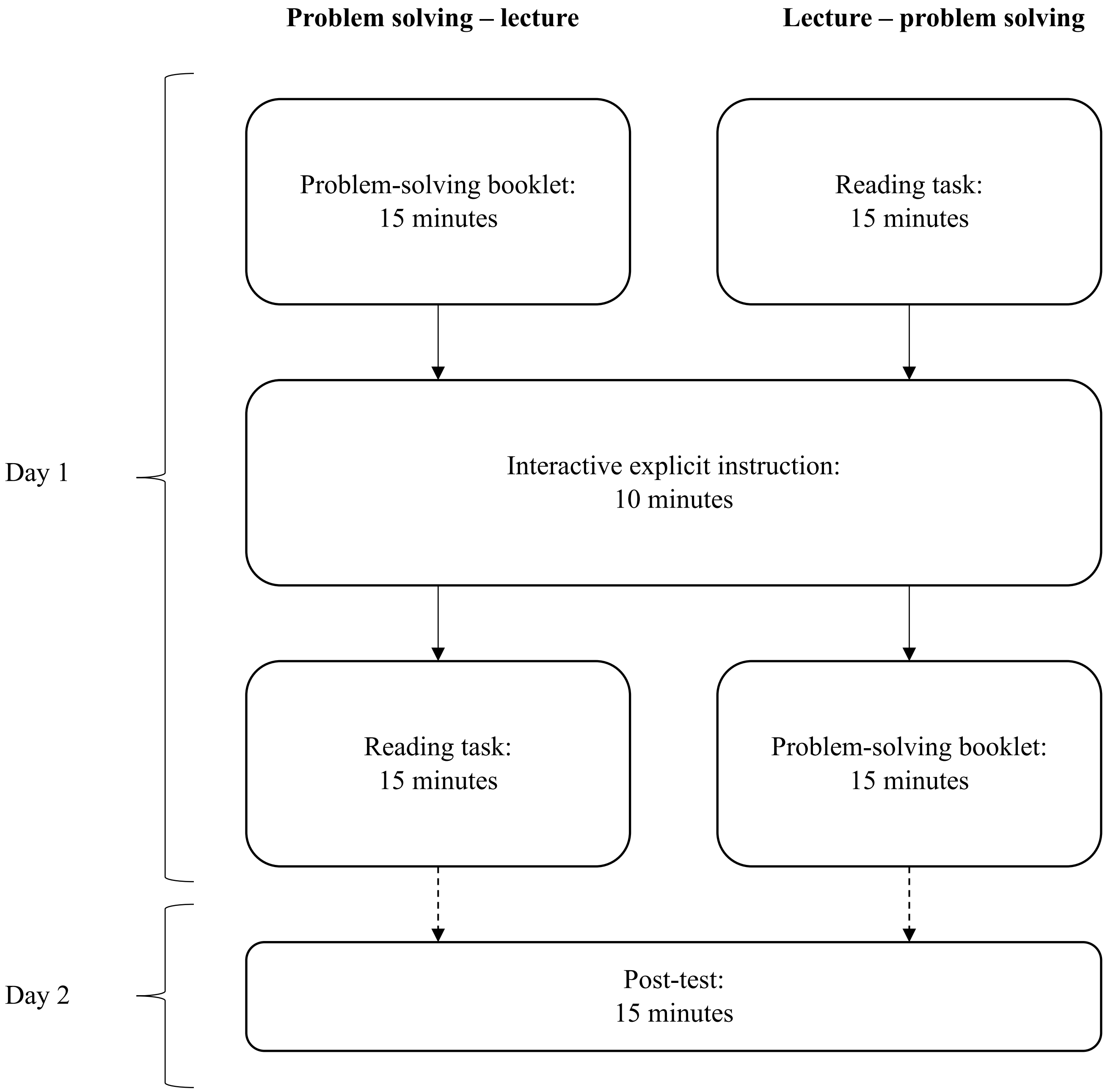

Figure 6.7.1 Procedure for Experiment 2

The inclusion of a reading filler task enabled the two conditions to be staggered in such a way that all 72 Year 5 students could receive the same live explicit instruction episode at the same time. In the Problem solving – lecture condition, 36 learners first completed a problem-solving booklet for 15 minutes. They then received interactive explicit instruction for 10 minutes alongside peers from the Lecture – problem solving condition before completing the reading filler task for 15 minutes. In the Lecture – problem solving condition, 36 learners first completed the reading filler task for 15 minutes, then participated in the interactive explicit teaching prior to completing the problem-solving booklet for 15 minutes. The problems again varied in the amount of relevant information provided, leading to approximately eight to twelve interacting elements. This took place during a scheduled science lesson.

The intended interactivity involved learners completing calculations on their calculators at the same time as the teacher and then holding these aloft. Learners then completed a post-test in a regular science lesson that took place the next day.

Although content was more targeted than in Experiment 1, the post-test still assessed a range of different objectives in order to attempt to assess transfer of learning. This led to only a moderately reliable Cronbach's α of .63.

Again, results were inconclusive, demonstrating no statistically significant difference between the two conditions, and learners did not achieve the intended outcomes, with mean scores on the post text of around 4 out of 16 for both conditions. This was likely caused by a flaw in the design. The treatment component of the experiment was scheduled for the last 40 minutes of a science lesson. During the explicit instruction phase, the instructor ran out of time before adequately demonstrating the method for calculating efficiency. Had time permitted, the explicit instruction phase could have expanded without introducing a confound because all students were in this phase together. However, the fact that the treatments was scheduled at the end of a science lesson meant there was no way to extend this phase.

The implications for Experiment 3 were clear. It would be necessary to provide ample time for the explicit instruction phase and, where possible, further reduce elements that were not directly relevant to the learning objective.

6.7.3 Experiment 3

In addition to testing the hypotheses described in section 6.6, a key minor objective of Experiment 3 was for a greater proportion of students to achieve the intended learning. As such, several changes were made.

Questions in the problem-solving booklet, explicit instruction phase and post-test were reduced to as low a literacy demand as possible. The post-test was given to learners in a science lesson that took place the next day and was split into two components. Each component lasted 15 minutes and Component 1 was completed and collected before Component 2 was distributed. The problem-solving booklet, the explicit instruction phase and Component 1 of the post-test focused entirely on calculating the energy efficiency of light globes through a series of isomorphic problems and examples, with all other learning objectives removed. The number of interacting elements required to be processed by this procedure was around eight. To test conceptual knowledge, Component 2 of the post-test consisted of near-transfer problems set in slightly different contexts e.g. fans instead of light globes, or with differing amounts of information present.

The procedure was like that for Experiment 2, with the same filler task used. A total of 69 Year 6 students participated, with 34 randomly assigned to the Problem solving – lecture condition and 35 assigned to the Lecture – problem solving condition.

There were no significant differences between the groups on either component of the post-test. For Component 1, the similar problems, the difference would have favoured the Lecture - problem solving condition on a one-tailed distribution. However, a one-tailed distribution could not be justified given that Productive Failure and Cognitive Load Theory imply effects operating in opposite directions. Items on the similar post-test component were highly reliable with Cronbach's α=.97 and items on the transfer post-test component were reliable with Cronbach's α=.82.

Pleasingly, the means for both conditions were proportionately higher than in the previous two experiments, indicating a greater amount of success on the post-test. However, on reviewing the post-test questions, a significant flaw in their design became apparent. As previously discussed, a common incorrect but intuitive solution method is to select the globe with the largest useful energy output as the one that is most 'energy saving'. Unfortunately, in the post-test, this often corresponded with the globe with the greatest efficiency. This meant that learners could select the correct answer for the wrong reason. This needed to be corrected in Experiment 4.

6.7.4 Experiment 4

Experiment 4 was similar to Experiment 3. There were three key differences. The problem-solving booklet, explicit teaching examples and similar questions in the post-test were altered to involve an additional step. Whereas, in Experiment 3, students were given the information about the useful light energy output of each globe, in Experiment 4 they had to compute this information from other values, using the law of the conservation of energy, requiring them to process around twelve interacting elements. Questions in the post-test improved so that there was no correspondence between answers arrived at from correct reasoning and reasoning that employed the common misconception highlighted above. To recognise the additional step, a different scoring system was employed that credited solution steps as well as solutions.

The additional step increased element interactivity and so, according to Cognitive Load Theory, should have been more favourable towards the Lecture – problem solving condition.

Participants were 71 Year 5 students, with 35 learners randomly allocated to the Problem solving – lecture condition and 36 learners allocated to the Lecture – Problem solving condition. The experiment followed the same procedure as Experiment 3, including the two-component post-test, consisting of similar and transfer questions, that the learners completed the following day.

Items on the similar post-test component were highly reliable with Cronbach's α=.96 and items on the transfer post-test component were highly reliable with Cronbach's α=.88. Results demonstrated a significant effect in favour of the Lecture – problem solving condition on both the similar post-test component ($t(69)=2.41$, $p= .02$, Cohen's $d=.57$) and the transfer post-test component ($t(69)=2.35$, $p= .02$, Cohen' s $d=.56$). These results are therefore consistent with the predictions of Cognitive Load Theory.

6.7.5 Experiment 5

The purpose of Experiment 5 was to investigate the effect of reducing the level of element interactivity on the relativeness effectiveness of the two conditions. In essence, the learning materials were like those used in Experiment 3 because the additional calculation step introduced in Experiment 4 was removed and useful output energy was simply presented to learners. This resulted in the number of interacting elements that learners needed to process being reduced back to eight, as in Experiment 3. However, the significant flaw in the design of Experiment 3 – learners may have obtained the right answer through faulty reasoning – was addressed.

Participants were 64 Year 5 students, with 30 learners randomly allocated to the Problem solving – lecture condition and 34 learners allocated to the Lecture – Problem solving condition. The experiment followed the same procedure as Experiments 3 and 4, including the two-component post-test. However, due to school timetabling considerations, learners did not complete this post-test until six days after the treatment.

Items on the similar post-test component were highly reliable with Cronbach's α=.94 and items on the transfer post-test component were highly reliable with Cronbach's α=.75. Results demonstrated a significant effect in favour of the Lecture – problem solving condition on the similar post-test component ($t(62)=2.25$, $p= .03$, Cohen's $d=.56$) but there was no significant effect on the transfer post-test component. The result for the similar post-test supports the prediction of Cognitive Load Theory. The results from the transfer post-test supports neither the predictions of Cognitive Load Theory nor Productive Failure.

6.8 Conclusions

The results of Experiment 1 and 2 do not provide firm evidence that is relevant to the hypothesis. Although a one-tailed distribution was not clearly justified, the fact that Experiment 3 demonstrated a significant result on a one-tailed distribution suggested that an effect favouring the predictions of Cognitive Load Theory may be obtainable on an experiment that removed the significant post-test design flaw of Experiment 3.

Experiments 4 and 5 demonstrated effects that supported the predictions of Cognitive Load Theory in three out of the four outcome measures and no effects that supported the predictions of Productive Failure. Moreover, taken together, the facts that target problems in Experiment 4 contained more element interactivity than in Experiment 5, and that both results were significant in Experiment 4 but only one was significant in Experiment 5, are suggestive that the greater the element interactivity, the more likely it is to obtain results favouring the Lecture – problem solving condition. This finding is consistent with a prediction of Cognitive Load Theory.

Taken together, these results provide evidence in support of the view that problem solving prior to explicit instruction overwhelms working memory when element interactivity is relatively high and that this impairs learning from a Problem solving – lecture sequence when compared to a Lecture – problem solving sequence.

Although these results do not provide any evidence to support or reject the use of Productive Failure in a context that is lower in element interactivity, it is worth stating that Productive Failure effects have been previously claimed in contexts where element interactivity is similar to the level of element interactivity in the above experiments, such as computing standard deviation (Kapur, 2014). These results therefore cast doubt on previous evidence for a Productive Failure effect in these contexts. This may be because Productive Failure effects are highly context specific.

Alternatively, these conflicting results may be due to the novel experimental design of Experiment 2-5 that allowed all learners to receive the same interactive explicit instruction at the same time, regardless of condition. If earlier studies were replicated using this design, it would reduce the potential for a confound whereby explicit instruction varied between conditions. Moreover, this method demonstrates potential for other research studies that contain elements of live, human-mediated teaching that cannot be strictly scripted and so contain some natural variation when repeated. If only one such episode is required for both conditions, small variations do not introduce confounds.

6.9 Limitations

In attempting to limit the potential confound of each condition having different explicit teaching experiences, the design of Experiments 2-5 introduces a different potential confound. The treatments of the two conditions are displaced by 15 minutes, with learners in the Problem solving – lecture condition beginning the treatment 15 minutes before learners in the Lecture – problem solving condition.

This would be a significant and perhaps fatal confound if the procedure deployed an immediate post-test. However, the use of consecutive science lessons enabled the post-test to take place the following day in most cases, and six days later in Experiment 5. With such a lag, the initial difference in timing between the two treatments is proportionately small.

Another way this time-lag could potentially affect learners is through fatigue (see e.g. Chen, Castro-Alonso, Paas, & Sweller, 2018), with learners in the Lecture – problem solving condition already having spent fifteen minutes on the reading task before their treatment began, in contrast to learners in the Problem solving – lecture condition going straight into the treatment. However, this would most likely degrade the learning of learners in the Lecture – problem solving condition relative to learners in the Problem solving – lecture condition. Where present, effects favoured the Lecture – problem solving condition and so any such fatigue effect would not call these results into question.

Conversely, learners in the Problem solving – lecture could have potentially suffered from an interference effect from the reading task completed after the treatment phase. If so, this could potentially account for the lower effectiveness of this condition. However, although a similar topic, the reading task was designed to not be directly relevant to the treatment materials and so would have a similar effect as when students move from one class to another, something that happened to both conditions during the course of the day of treatment.

6.10 Suggestions for further research

This experimental design could be extended to other areas. For instance, composing a paragraph is generally a high element interactivity task. Although the elements cannot easily be counted, the contents of a sentence and, by extension, a paragraph, are dependent on each other. For example, altering the opening sentence will have an impact on subsequent sentences. It would therefore be possible to use this design to test the effect of open-ended paragraph construction followed by explicit teaching in how to construct a paragraph versus the opposite sequence. Contexts could be drawn from informative, persuasive or narrative writing, or from a domain area such as history. Alternatively, instead of varying the context, it could be possible to reduce the element interactivity from the relatively high level present in the current experiment.

Problem solving frequently involves deploying a number of related steps. Examples of tasks that have elicited a 'generation effect' are usually low in element interactivity. For instance, Hirschmann and Bjork (1988) required subject to memorise lists of associated word pairs such as 'sickness' and 'health'. In the control condition, participants were simply presented with a list of the word pairs. In the generative condition, participants were asked to generate the second word. This is a low element interactivity task because each word pair consists of two words and a relationship, with no word pair interacting with any other word pair. Therefore, one way of extending these findings would be to find educationally relevant learning objectives with similarly low levels of intrinsic complexity as the word pair task. For example, in the context of the learning objectives in this experiment, learners could simply memorise the equation defining efficiency. In this case, by reducing element interactivity, we may expect to find a Productive Failure effect.

Rather than reducing element interactivity by reducing the complexity of materials, an alternative may be to increase the level of expertise of the learners (Chen, Kalyuga, & Sweller, 2017). If learners had prior experience with the subject content and solution methods then they would have developed schemas for these, reducing the number of elements to be processed in working memory. Consistent with the predictions of Cognitive Load Theory, we may find that problem solving prior to explicit teaching is more effective than the reverse order in an effect similar to the expertise reversal effect (Kalyuga, Ayres, Chandler, & Sweller, 2003).

For high expertise learners, the lecture phase in such an experiment is likely to be redundant, but a problem-solving phase prior to the lecture phase may work as posited in Productive Failure to highlight any remaining knowledge gaps and therefore target attention to these remaining gaps in the lecture phase.

The context of writing offers the possibility of varying a number of these factors in a 2×2 design. Variations may result from interactions of learner expertise and context. For instance, learners could be fluent in the process of writing, in the context of the writing, both or neither. Fluency in the context could be manipulated by alternating between a biologically primary context – such as a narrative about a relationship – and a biologically secondary context – such as a discussion of energy generation. For fluent writers, writing about a biologically primary context would represent the lowest element interactivity context, but the potential differential effects of skill expertise versus domain expertise could be investigated.

In conclusion, this thesis indicates that for high element interactivity information, a lecture preceding problem solving is preferable to the reverse sequence. The generality of this finding will require further work as indicated above.

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Appendix 1
Experiment 1 Materials

1. Post-test

Student number:

Quiz Booklet

This quiz is to inform the research project and will not count towards any school assessment

Please answer as many questions as you can in the available time

Question 1
Which is the best description of kinetic energy? (please circle)

A. The energy that a moving object has

B. The energy that an object gains when you lift it higher

C. The energy given out by a hot object

D. The energy given out when a squashed spring is released

Question 2
What is the best description of what happens as an object falls? (please circle)

A. It loses kinetic energy

B. It gains gravitational potential energy

C. It loses elastic potential energy

D. It loses gravitational potential energy

Question 3
Which statement about energy is true? (please circle)

A. Energy is created in the Sun

B. Energy will eventually run out

C. Energy cannot be created or destroyed

D. The total amount of energy is always increasing

Question 4
Which of these is **not** an example of a machine? (please circle)

A. Electric Fan

B. Light globe

C. Clock

D. Book

Question 5
What is the useful energy given out by a radio? (please circle)

A. Light

B. Heat

C. Sound

D. Electrical energy

Question 6
A light globe takes in 100 joules of electric energy and gives out 30 joules of light energy and 70 joules of heat energy. What is its efficiency? (please circle)

A. 60%

B. 30%

C. 70%

D. 20%

Question 7
An electric fan takes in 150 joules of electrical energy and gives out 120 joules of heat and sound energy. What is its efficiency? (please circle)

A. 20%

B. 40%

C. 60%

D. 80%

Question 8
A solar panel converts light energy into electrical energy with an efficiency of 60%. How much electrical energy will it produce from 200 joules of light energy?

A. 120 joules

B. 180 joules

C. 60 joules

D. 80 joules

Question 9
Charlie has to decide which brand of light globes to put in to his new kitchen. He wants the most efficient bulbs that he can find.

He decided to test each globe by using it to heat up water for one minute. This way, he could work out how much electrical energy each globe took in per minute and how much heat energy each globe gave out per minute.

Charlie got the following results:

Brand	Electrical taken in per minute (joules)	Heat energy given out per minute (joules)		
A	4000	3000		
B	4000	2000		
C	2000	400		
D	1000	500		

Which brand of globes should Charlie buy? (please circle)

A B C D

Question 10
Maria wants to use an electric fan in her office in the summer. Electric fans produce heat energy and kinetic energy.

Below is a list of fans that Maria could choose from.

Fan	Heat energy given out per second (joules)	Kinetic energy given out per minute (joules)		
A	30	6		
B	30	12		
C	10	5		
D	10	10		

Two questions here

a) Which fan produces the most useful energy per second? (please circle)

A B C D

b) Which fan is the most efficient? (please circle)

A B C D

Question 11

Afsha wants to choose the most energy efficient radio for her office.

Below is a list of radios that Afsha could choose from.

Fan	Heat energy given out per second (joules)	Kinetic energy given out per minute (joules)		
A	15	5		
B	20	10		
C	15	10		
D	20	6		

Two questions here

a) Which radio produces the least amount of useful energy per second? (please circle)

A B C D

b) Which radio is the most efficient? (please circle)

A B C D

Question 12

A number of different LED lights are tested. Complete the table below to fill in the missing values. You may use the space below the table for any workings.

LED	Electrical energy taken in per second (joules)	Light energy given out per second (joules)	Heat energy given out per second (joules)	Efficiency
A	16	12		
B	16		8	
C	25			80%
D	30			70%
E		12		60%

2. Explicit instruction slides

Slide 1

Energy

This video is a few minutes long and you will need to read along.

Please try your best to follow it.

Slide 2

Energy

Energy cannot be created or destroyed; it can only be turned from one form into another.

Slide 3

Types of energy

Heat energy

This flows from warm objects to cooler objects. If you give heat energy to something then it will increase in temperature.

Light energy

This is energy that is transferred from one place to another in the form of light.

Sound energy

This is energy that is transferred from one place to another in the form of sound.

Electrical energy

This is energy that is transferred by an electric current in an electrical circuit.

Slide 4

Types of energy

Kinetic energy

This is the energy that a moving object has.

Gravitational Potential Energy

This is the energy that is stored by holding an object above the ground. We know that energy must be stored because if we let the object fall then it will speed up and so its kinetic energy will increase. In other words, if we let go then energy will be released.

Elastic Potential Energy

This is the energy stored when we stretch something or squash something. We know energy is stored because if we let go then that energy will be released.

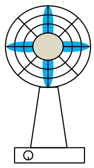
Slide 5

What is a machine?

In science, a machine is *anything* that changes one type of energy into another.

This includes things that you might already think of as machines such as an electric fan.

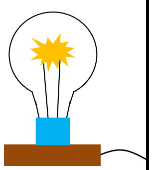
Electric fans change electrical energy into kinetic energy as well as heat and sound energy.



Slide 6

What is a machine?

However, a light globe is *also* a machine because it changes electrical energy into heat energy and light energy.



Slide 7

Efficiency

Some of the energy changes that take place in a machine are useful and some of them are not useful.

We can calculate something known as the ***efficiency*** for a machine.

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 8

Example 1

Which is the most efficient light globe?

Light Globe	Electrical energy taken in per minute (joules)	Heat energy given out per minute (joules)	Light energy given out per minute (joules)
A	1000 =	600 +	400
B	1000 =	400 +	600
C	2000 =	800 +	1200
D	2000 =	500 +	1500

First, notice that the energy given out **must always** equal the energy taken in.

This can be useful to know if you don't know one of the values. You can use this to work out missing values.

Slide 9

Example 1

Which is the most efficient light globe?

Light Globe	Electrical energy taken in per minute (joules)	Heat energy given out per minute (joules)	Light energy given out per minute (joules)
A	1000	600	400
B	1000	400	600
C	2000	800	1200
D	2000	500	1500

<u>To find the efficiency of Globe A:</u>

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$

The useful energy given out by a light globe is light energy.

Slide 10

Example 1

Which is the most efficient light globe?

Light Globe	Electrical energy taken in per minute (joules)	Heat energy given out per minute (joules)	Light energy given out per minute (joules)
A	1000	600	400
B	1000	400	600
C	2000	800	1200
D	2000	500	1500

To find the efficiency of Globe A:

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$

$$Efficiency = \frac{400}{1000} \times 100\% = 0.4 \times 100\% = 40\%$$

Slide 11

Example 1

Which is the most efficient light globe?

Light Globe	Electrical energy taken in per minute (joules)	Heat energy given out per minute (joules)	Light energy given out per minute (joules)	Efficiency
A	1000	600	400	40%
B	1000	400	600	
C	2000	800	1200	
D	2000	500	1500	

To find the efficiency of Globe B:

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$

$$Efficiency = \frac{600}{1000} \times 100\% = 0.6 \times 100\% = 60\%$$

Slide 12

Example 1

Which is the most efficient light globe?

Light Globe	Electrical energy taken in per minute (joules)	Heat energy given out per minute (joules)	Light energy given out per minute (joules)	Efficiency
A	1000	600	400	40%
B	1000	400	600	60%
C	2000	800	1200	
D	2000	500	1500	

To find the efficiency of Globe C:

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$

$$Efficiency = \frac{1200}{2000} \times 100\% = 0.6 \times 100\% = 60\%$$

Slide 13

Example 1

Which is the most efficient light globe?

Light Globe	Electrical energy taken in per minute (joules)	Heat energy given out per minute (joules)	Light energy given out per minute (joules)	Efficiency
A	1000	600	400	40%
B	1000	400	600	60%
C	2000	800	1200	60%
D	2000	500	1500	

To find the efficiency of Globe D:

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$

$$Efficiency = \frac{1500}{2000} \times 100\% = 0.75 \times 100\% = 75\%$$

Slide 14

Example 1

Which is the most efficient light globe?

Light Globe	Electrical energy taken in per minute (joules)	Heat energy given out per minute (joules)	Light energy given out per minute (joules)	Efficiency
A	1000	600	400	40%
B	1000	400	600	60%
C	2000	800	1200	60%
D	2000	500	1500	75%

The most efficient light globe is therefore Globe D

Slide 15

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)		
A	500	200		
B	500	250		
C	800	200		
D	800	400		

First, we need to calculate the useful, *kinetic* energy given out by each fan. We can do this because we know that heat and sound energy *plus* kinetic energy must equal the electrical energy used.

Slide 16

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	
A	500	200		
B	500	250		
C	800	200		
D	800	400		

Fan A

$$500 - 200 = 300$$

Slide 17

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	
A	500	200	300	
B	500	250		
C	800	200		
D	800	400		

Fan B

$$500 - 250 = 250$$

Slide 18

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	
A	500	200	300	
B	500	250	250	
C	800	200		
D	800	400		

Fan C

$$800 - 200 = 600$$

Slide 19

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	
A	500	200	300	
B	500	250	250	
C	800	200	600	
D	800	400		

Fan D

$$800 - 400 = 400$$

Slide 20

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	
A	500	200	300	
B	500	250	250	
C	800	200	600	
D	800	400	400	

We can now work out the efficiency of each fan

Slide 21

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	Efficiency
A	500	200	300	
B	500	250	250	
C	800	200	600	
D	800	400	400	

Fan A

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$
$$= \frac{300}{500} \times 100\% = 60\%$$

Slide 22

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	Efficiency
A	500	200	300	60%
B	500	250	250	
C	800	200	600	
D	800	400	400	

Fan B

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$

$$= \frac{250}{500} \times 100\% = 50\%$$

Slide 23

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	Efficiency
A	500	200	300	60%
B	500	250	250	50%
C	800	200	600	
D	800	400	400	

Fan C

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$

$$= \frac{600}{800} \times 100\% = 75\%$$

Slide 24

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	Efficiency
A	500	200	300	60%
B	500	250	250	50%
C	800	200	600	75%
D	800	400	400	

Fan D

$$Efficiency = \frac{useful\ energy\ out}{total\ energy\ in} \times 100\%$$

$$= \frac{500}{800} \times 100\% = 50\%$$

Slide 25

Example 2

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)	Kinetic energy given out per minute (joules)	Efficiency
A	500	200	300	60%
B	500	250	250	50%
C	800	200	600	75%
D	800	400	400	50%

The most efficient fan is Fan C

3. Problem-solving booklet

Student number:

Problem Solving Booklet

Try the problems in this book.

You are not expected to answer all of them and you are not expected to get the right answers

The idea of the booklet is to help with your learning

You will be asked to stop after ten minutes

Light Globes

Maria has to decide which brand of light globes to put in to her new kitchen. She wants the most efficient bulbs that she can find.

She decided to test each globe by using it to heat up water for one minute. This way, she could work out how much electrical energy each globe took in per minute and how much heat energy each globe gave out per minute.

Maria got the following results:

Light Globe	Electrical energy taken in per minute (joules)	Heat energy given out per minute (joules)		
A	1000	200		
B	1000	500		
C	2000	600		
D	2000	800		

Which brand of light globes is the most efficient?

A **B** **C** **D**

Explain your answer

____

____

____

Plasma TVs

Plasma televisions give out a lot of energy as heat. The rest is given out as light in the picture and sound in the speakers.

Jane looked at the energy efficiency information for a range of different plasma televisions.

The table below shows what Jane found out:

Television	Electrical energy taken in per second (joules)	Heat energy given out per second (joules)		
A	140	70		
B	140	105		
C	210	105		
D	210	140		

Which brand of light globes is the most efficient? (circle)

A **B** **C** **D**

Explain your answer

____

____

____

Fans

Electric fans take in electrical energy and give out heat, sound and kinetic energy. Which model is the most efficient?

Model	Electrical energy used per minute (joules)	Heat and sound energy given out per minute (joules)		
A	500	200		
B	500	300		
C	800	200		
D	800	400		

Which model of fan is the most efficient?

A **B** **C** **D**

Explain your answer

____

____

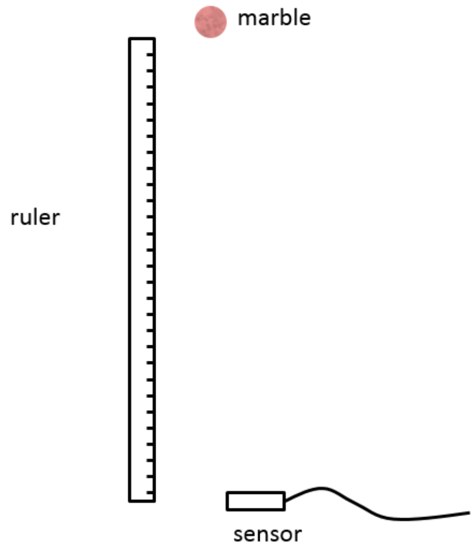
____

Marbles

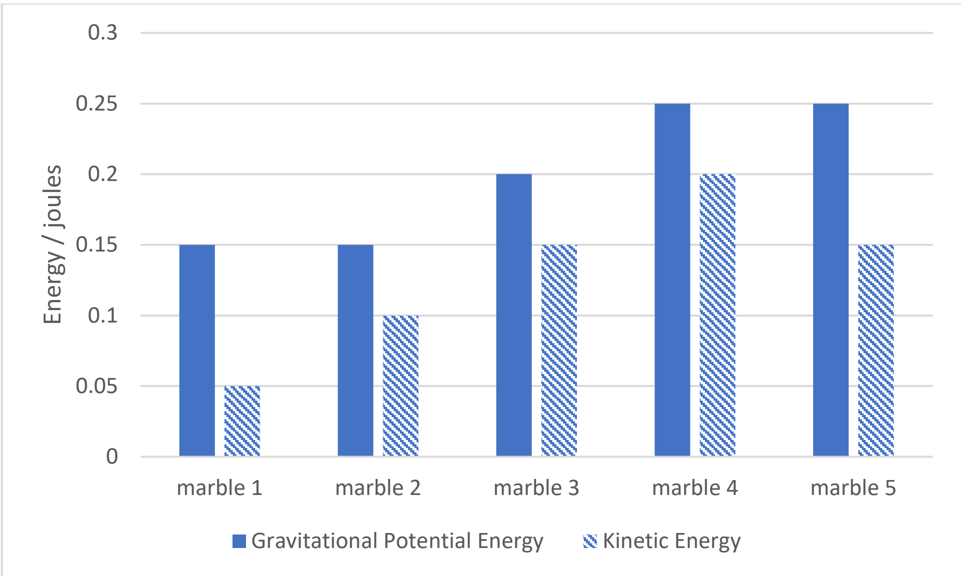
Shayne and Anna dropped different shaped marbles from different heights.

They measured the mass of each marble and calculated the amount of gravitational potential energy the each marble had at the start of each drop. They used a sensor to measure the speed of each marble at the bottom of the drop and from this they calculated the kinetic energy of each marble at the bottom of the drop.

They used the following apparatus:



They obtained the following results:

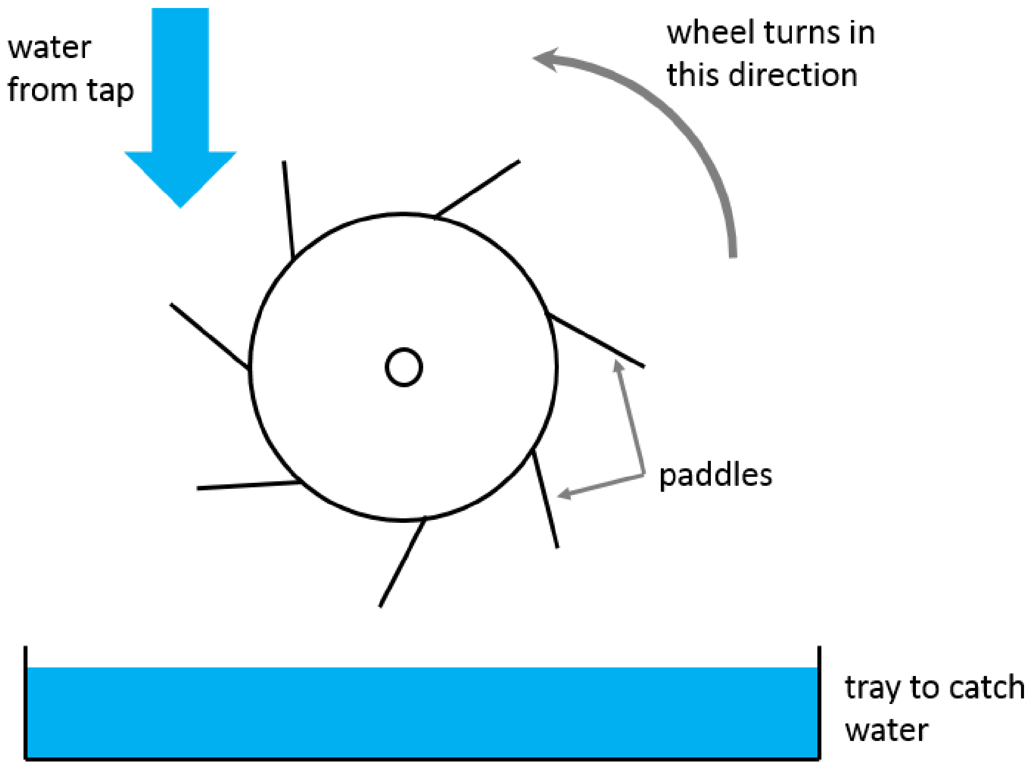


Which marble converted the smallest proportion of its gravitational potential energy into heat and sound energy?

Water Wheel

A water wheel is designed to convert gravitational potential energy stored in water into kinetic energy the wheel. As it turns, the water wheel's bearing gets warm and a splashing sound can be heard.

Lachlan and Suleiman build a model water wheel in their science lesson as in the diagram below. A clamp holds the axle of the wheel in place. A computer sensor is used to find the speed of the wheel.



Lachlan and Suleiman changed the number of paddles and wrote down their observations. In each design, the water wheel turned at the same speed. Changing the number of paddles does not affect the mass of the wheel.

Test	Number of paddles	How does the bearing feel after one minute?	Loudness of splashing
A	4	cool	loud
B	6	cool	quiet
C	8	warm	quiet
D	10	warm	loud

In which test did the number of paddles make the water wheel the most efficient?

Appendix 2
Experiment 2 Materials

1. Post-test

Name – Please write in box below

Condition – Please Circle

P	Q

Assessment

Booklet

Question 1

James wants to replace the old light globes in his kitchen with new energy saving globes. He may choose to use more globes or fewer globes in order to keep the amount of light the same.

Light globes take in electrical energy and give out heat and light energy.

James has the following information that he can use to make his choice between Globes A and B. The amount of energy is measured in joules which have the symbol 'J'.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	40 J	24 J	16 J
B	20 J	10 J	10 J

Which globe should he choose?

…………

Why should he choose this globe?

………

………

James is now offered a third Globe to choose from, Globe C. The following information compares Globes A, B and C

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	40 J	24 J	16 J
B	20 J	10 J	10 J
C	30 J	12 J	18 J

Which globe should he choose?

…………

Why should he choose this globe?

………

………

TURN OVER FOR NEXT QUESTION

Question 2

Yasmine wants to replace the old light globes in her lounge room with new energy saving globes. She may choose to use more globes or fewer globes in order to keep the amount of light the same.

Light globes take in electrical energy and give out heat and light energy.

Yasmine has the following information that she can use to make her choice between Globes A, B and C. The amount of energy is measured in joules which have the symbol 'J'.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	40 J	20 J	20 J
B	30 J	15 J	15 J
C	40 J	16 J	24 J

Which globe should she choose?

……………

Why should she choose this globe?

……..

…….

TURN OVER FOR NEXT QUESTION

Question 3

Ahmed wants to use the most energy saving fan in his new deck area.

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Ahmed has the following information that he can use to make his choice between Fans A, B and C. The amount of energy is measured in joules which have the symbol 'J'.

The column for the amount of movement energy has been left blank.

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	150 J	96 J	
B	100 J	80 J	
C	100 J	70 J	

Which fan should he choose?

…………..

Why should he choose this fan?

……..

………

TURN OVER FOR NEXT QUESTION

Question 4

Jane wants to use the most energy saving fan in her new study

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Jane has the following information that she can use to make her choice between Fans A, B and C. The amount of energy is measured in joules which have the symbol 'J'.

The column for the amount of movement energy has been left blank.

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	90 J	45 J	
B	75 J	45 J	
C	100 J	55 J	

Which fan should she choose?

…………..

Why should she choose this fan?

………..

………..

TURN OVER FOR NEXT QUESTION

Question 5

Have a look at the information about five light globes that is given below.

The column for the light energy given out per second has been left blank.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	60 J	30 J	
B	80 J	60 J	
C	60 J	24 J	
D	80 J	28 J	
E	80 J	40 J	

Which is the most energy saving globe?

……………

How do you know?

……..

……….

TURN OVER FOR NEXT QUESTION

Question 6

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Below is some information about different types of fan.

Some of the information is missing.

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	75 J		30 J
B		80 J	20 J
C	100 J	70 J	
D	100 J	90 J	
E		63 J	27 J
F	80 J		28 J

Which is the *most* energy saving fan?

……………

How do you know?

……

……

Which is the *least* energy saving fan?

……………

How do you know?

……

……

END OF QUESTIONS

2. Explicit instruction slides

Slide 1

Saving Energy

Slide 2

Task 1

Slide 3

Energy

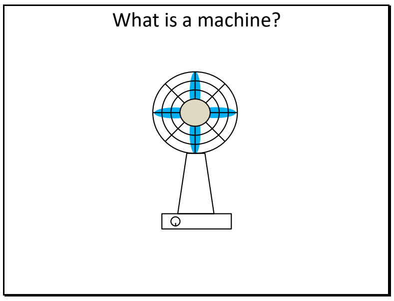
Energy cannot be created or destroyed; it can only be turned from one form into another.

Slide 4

Types of energy
1. Heat energy
2. Light energy
3. Sound energy
4. Electrical energy
5. Kinetic (movement) energy
6. Gravitational Potential Energy
7. Elastic Potential Energy

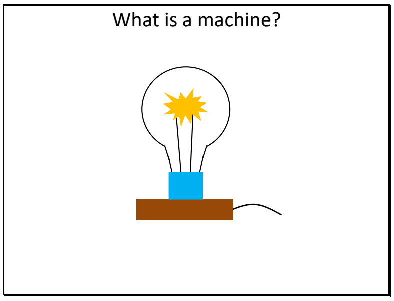
<u>Heat energy</u>
This flows from warm objects to cooler objects. If you give heat energy to something then it will increase in temperature.
<u>Light energy</u>
This is energy that is transferred from one place to another in the form of light.
<u>Sound energy</u>
This is energy that is transferred from one place to another in the form of sound.
<u>Electrical energy</u>
This is energy that is transferred by an electric current in an electrical circuit.
<u>Kinetic energy</u>
This is the energy that a moving object has.
<u>Gravitational Potential Energy</u>
This is the energy that is stored by holding an object above the ground. We know that energy must be stored because if we let the object fall then it will speed up and so its kinetic energy will increase. In other words, if we let go then energy will be released.
<u>Elastic Potential Energy</u>
This is the energy stored when we stretch something or squash something. We know energy is stored because if we let go then that energy will be released.

Slide 5



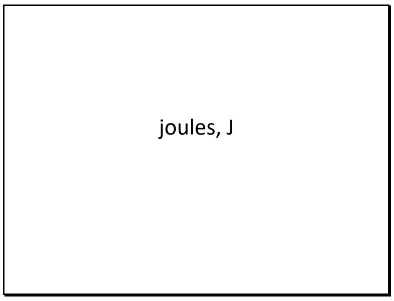
In science, a machine is *anything* that changes one type of energy into another.
This includes things that you might already think of as machines such as an electric fan.
Electric fans change electrical energy into kinetic energy as well as heat and sound energy.

Slide 6



However, a light globe is *also* a machine because it changes electrical energy into heat energy and light energy.

Slide 7



Energy is often measured in joules which have the symbol "J"

Slide 8

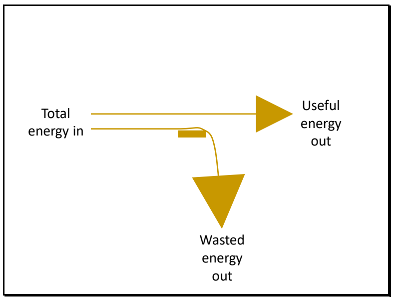
Energy saving light globes

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60J	30J	30J
B	60J	45J	15J
C	50J	28J	22J

Consider this question.

Slide 9



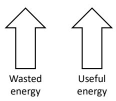
This diagram gives us a way to picture how energy is transformed by machines

Slide 10

Energy saving light globes

Which globe saves the most energy?

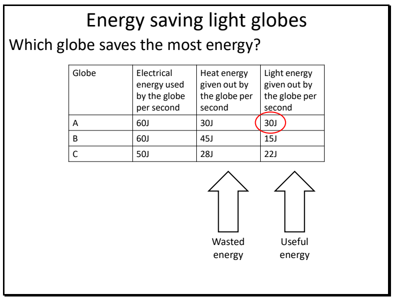
Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60J	30J	30J
B	60J	45J	15J
C	50J	28J	22J



The useful energy given out by light globe is light energy

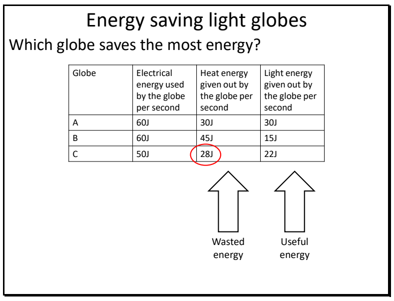
The wasted energy given out by a light globe is heat energy

Slide 11



Some people think it's the globe that produces the greatest amount of useful light energy

Slide 12



Some people think it's the globe that wastes the least energy as heat.

Slide 13

Slide 14

Efficiency

We can work out the proportion of the energy that is converted into useful energy.

To do this, we calculate something known as the ***efficiency*** for the machine.

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 15

Energy saving light globes

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60J	30J	30J
B	60J	45J	15J
C	50J	28J	22J

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 16

Energy saving light globes

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60J	30J	30J
B	60J	45J	15J
C	50J	28J	22J

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 17

Energy saving light globes

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60J	30J	30J
B	60J	45J	15J
C	50J	28J	22J

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 18

Energy saving light globes

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60J	30J	30J
B	60J	45J	15J
C	50J	28J	22J

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 19

Remember:
Energy cannot be created or destroyed; it can only be turned from one form into another.

Slide 20

The noisy fan

Which electric fan is the most efficient?

Globe	Electrical energy used by the fan per second	Heat and sound energy given out by the fan per second	Movement energy given out by the fan per second
A	100J	55J	
B	80J	48J	
C	100J	50J	

Electric fans work by turning electrical energy into kinetic (movement) energy. They also waste quite a lot of energy as heat and sound.
Now that we know about energy, we can replace the question “which fan saves the most energy?” with “which fan is the most efficient?”

Slide 21

The noisy fan

Which electric fan is the most efficient?

Globe	Electrical energy used by the fan per second	Heat and sound energy given out by the fan per second	Movement energy given out by the fan per second
A	100J	55J	
B	80J	48J	
C	100J	50J	

Slide 22

The noisy fan

Which electric fan is the most efficient?

Globe	Electrical energy used by the fan per second	Heat and sound energy given out by the fan per second	Movement energy given out by the fan per second
A	100J	55J	45J
B	80J	48J	
C	100J	50J	

Slide 23

The noisy fan

Which electric fan is the most efficient?

Globe	Electrical energy used by the fan per second	Heat and sound energy given out by the fan per second	Movement energy given out by the fan per second
A	100J	55J	45J
B	80J	48J	32J
C	100J	50J	

Slide 24

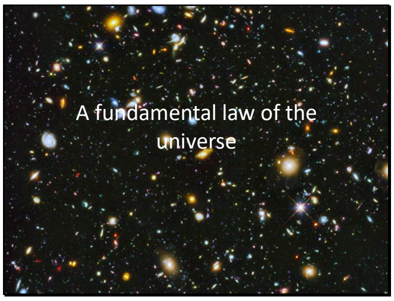
The noisy fan

Which electric fan is the most efficient?

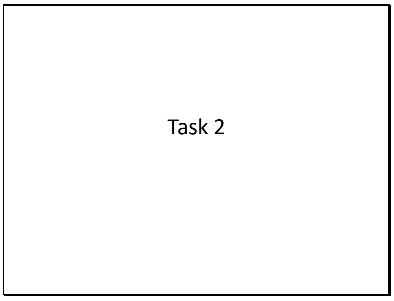
Globe	Electrical energy used by the fan per second	Heat and sound energy given out by the fan per second	Movement energy given out by the fan per second
A	100J	55J	45J
B	80J	48J	32J
C	100J	50J	50J

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 25



Slide 26



3. Problem-solving booklet

Name – Please write in box below

Condition – Please Circle

P	Q

Problem Solving Booklet

This booklet contains some problems to try to solve.

They are set in everyday situations so have a think how you would solve the problem in real life.

You are not expected to solve all of the problems. Just do what you can.

Problem 1 – Light globes in the kitchen

John wants to replace the old light globes in his kitchen with new energy saving globes. He may choose to use more globes or fewer globes in order to keep the amount of light the same.

Light globes take in electrical energy and give out heat and light energy.

John has the following information that he can use to make his choice between Globes A and B. The amount of energy is measured in joules which have the symbol 'J'.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 J	12 J	18 J
B	15 J	9 J	6 J

Which globe should he choose?

……………

Why should he choose this globe?

………..

………..

John is now offered a third Globe to choose from, Globe C. The following information compares Globes A, B and C

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 J	12 J	18 J
B	15 J	9 J	6 J
C	20 J	10 J	10 J

Which globe should he choose?

……………

Why should he choose this globe?

………..

………..

Problem 2 – Light globes in the lounge room

Anita wants to replace the old light globes in her lounge room with new energy saving globes. She may choose to use more globes or fewer globes in order to keep the amount of light the same.

Light globes take in electrical energy and give out heat and light energy.

Anita has the following information that she can use to make her choice between Globes A, B and C. The amount of energy is measured in joules which have the symbol 'J'.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 J	15 J	15 J
B	20 J	8 J	12 J
C	30 J	18 J	12 J

Which globe should she choose?

……………

Why should she choose this globe?

……..

…….

Problem 3 – Fans

John wants to use the most energy saving fan in his new deck area.

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as ‘kinetic energy’).

John has the following information that he can use to make his choice between Fans A, B and C. The amount of energy is measured in joules which have the symbol ‘J’.

The column for the amount of movement energy has been left blank.

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	100 J	80 J	
B	150 J	96 J	
C	100 J	70 J	

Which fan should he choose?

…………..

Why should he choose this fan?

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………

Problem 4 – Fans

Maxine wants to use the most energy saving fan in her new study

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Maxine has the following information that she can use to make her choice between Fans A, B and C. The amount of energy is measured in joules which have the symbol 'J'.

The column for the amount of movement energy has been left blank.

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	80 J	64 J	
B	75 J	57 J	
C	100 J	75 J	

Which fan should she choose?

…………..

Why should she choose this fan?

………..

………..

Problem 5 – Light globes

Have a look at the information about five light globes that is given below.

The column for the light energy given out per second has been left blank.

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	60 J	42 J	
B	50 J	40 J	
C	60 J	54 J	
D	50 J	42 J	
E	60 J	48 J	

Which is the most energy saving globe?

……………

How do you know?

……..

……….

Problem 6 – Fans

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Below is some information about different types of fan.

Some of the information is missing.

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A		80 J	20 J
B	75 J		30 J
C	100 J	90 J	
D	100 J	70 J	
E	80 J		28 J
F		63 J	27 J

Which is the *most* energy saving fan?

……………

How do you know?

……

……

Which is the *least* energy saving fan?

……………

How do you know?

……

……

Appendix 3
Experiment 3 Materials

1. Post-test Component 1

Similar Questions

Name – Please write in box below

Condition – Please Circle

P	Q

Assessment Component 1

Booklet

Problem 1 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	20 joules	10 joules	10 joules
B	15 joules	9 joules	6 joules
C	30 joules	12 joules	8 joules

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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Problem 2 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 joules	15 joules	15 joules
B	30 joules	18 joules	12 joules
C	20 joules	8 joules	12 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	80 joules	20 joules
B	100 joules	70 joules	30 joules
C	150 joules	96 joules	54 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	75 joules	25 joules
B	75 joules	57 joules	18 joules
C	80 joules	64 joules	16 joules
D	100 joules	74 joules	26 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 5 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	60 joules	42 joules	18 joules
B	50 joules	42 joules	8 joules
C	60 joules	54 joules	6 joules
D	50 joules	40 joules	10 joules
E	60 joules	48 joules	12 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 6 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	75 joules	45 joules	30 joules
B	80 joules	52 joules	28 joules
C	100 joules	80 joules	20 joules
D	100 joules	90 joules	10 joules
E	100 joules	70 joules	30 joules
F	90 joules	63 joules	27 joules

Which is the **most** energy saving globe?

……………

Which is the **least** energy saving globe?

……………

You may use the space below to do any calculations

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2. Post-test Component 2

Transfer Questions

Name – Please write in box below

Condition – Please Circle

P	Q

Assessment Component 2

Booklet

15 minutes

Please use a calculator

Problem 1

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	150 joules	96 joules	54 joules
B	100 joules	80 joules	20 joules
C	100 joules	70 joules	30 joules

Which is the **most** energy saving fan?

……………

You may use the space below for any calculations

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Which is the **least** energy saving fan?

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You may use the space below for any calculations

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Problem 2

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Globe	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	90 joules	45 joules	45 joules
B	75 joules	45 joules	30 joules
C	100 joules	55 joules	45 joules

Which is the **most** energy saving fan?

……………

You may use the space below for any calculations

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Which is the **least** energy saving fan?

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You may use the space below for any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	50 joules	
B	100 joules	70 joules	
C	150 joules	90 joules	

The last column has not been completed in the table.

Complete the last column using the fact that the total energy given out must equal the total energy used.

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

…………..

You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	65 joules	
B	80 joules	64 joules	
C	75 joules	57 joules	
D	100 joules	70 joules	

The last column has not been completed in the table.

Complete the last column using the fact that the total energy given out must equal the total energy used.

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 5 - Leaf Blower

Electric leaf blowers are noisy. They take in electrical energy and give out heat, sound and kinetic energy. Skye and Ananth look at some information about leaf blowers.

Leaf Blower	Electrical energy used by the leaf blower per second	Heat and sound energy given out by the leaf blower per second
Brand A	200 joules	150 joules
Brand B	200 joules	120 joules

Skye says, “Brand B is the most efficient leaf blower because it gives out the least energy as heat and sound.”

Ananth says, “No, you cannot know which is the most efficient because you don’t know how much useful energy is given out by each leaf blower.”

Who do you agree with? …………………………

Explain why

………

………

………

………

Problem 6 - Efficient Cars

Jasmine decides to buy a new car. Cars get chemical energy from fuel.

She decides that she wants an energy efficient car. She looks up information on the average volume of fuel that each car uses to travel 100 km.

Car	Average volume of fuel used to travel 100 km
Mitsubishi Outlander	1.9 litres
Audi A3	1.7 litres
Volvo XC90	2.1 litres

Which car is the most energy efficient? …………

Explain your answer

……

……

……

……

Problem 7 - Solar heating system

A solar heating system is made of a panel that sits on the roof of a house. Water passes through this panel.

If the solar heating system is very efficient then which of the following is true?

a. Little of the heat energy from the Sun is converted to heat energy in the water
b. Lots of the heat energy from the Sun is converted to movement energy in the water
c. Lots of the heat energy from the Sun is converted into heat energy in the water
d. Little of the movement energy from the Sun is converted heat energy in the water

Problem 8 - Battery Homework

Justin is completing a research activity on batteries for his science homework.

He writes the following:

> Batteries create the energy used by electrical devices. Some electrical devices need more energy and so they need bigger batteries.

Justin is wrong.

Explain why Justin is wrong

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3. Explicit instruction slides

Slide 1

Saving Energy

Slide 2

Task 1

Slide 3

Energy

Energy cannot be created or destroyed; it can only be converted from one form into another.

Slide 4

Types of energy

1. Heat energy
2. Light energy
3. Sound energy
4. Electrical energy
5. Movement energy
6. Gravitational Potential Energy
7. Elastic Potential Energy

Heat energy

This flows from warm objects to cooler objects. If you give heat energy to something then it will increase in temperature.

Light energy

This is energy that is transferred from one place to another in the form of light.

Sound energy

This is energy that is transferred from one place to another in the form of sound.

Electrical energy

This is energy that is transferred by an electric current in an electrical circuit.

Kinetic energy

This is the energy that a moving object has.

Gravitational Potential Energy

This is the energy that is stored by holding an object above the ground. We know that energy must be stored because if we let the object fall then it will speed up and so its kinetic energy will increase. In other words, if we let go then energy will be released.

Elastic Potential Energy

This is the energy stored when we stretch something or squash something. We know energy is stored because if we let go then that energy will be released.

Slide 5

joules

Energy is often measured in joules which have the symbol “J”

Slide 6

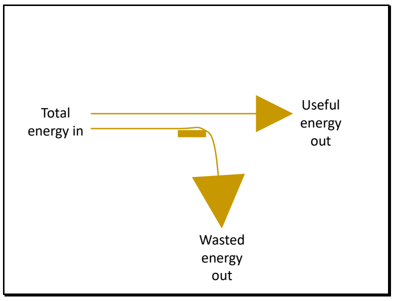
Energy saving light globes

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules

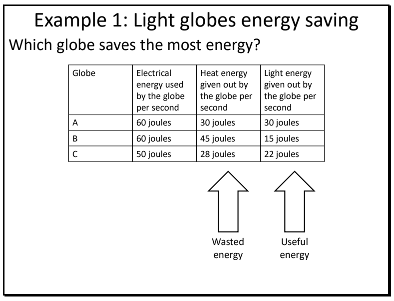
Consider this question.

Slide 7



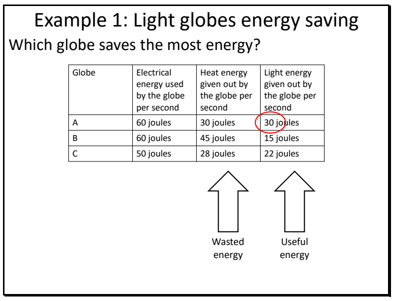
This diagram gives us a way to picture how energy is transformed by machines

Slide 8



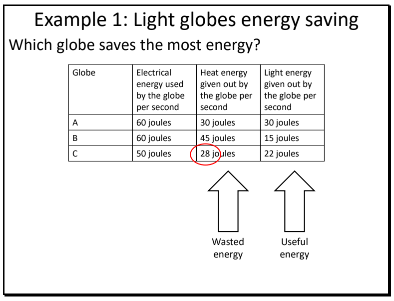
The useful energy given out by light globe is light energy
The wasted energy given out by a light globe is heat energy

Slide 9



Some people think it's the globe that produces the greatest amount of useful light energy

Slide 10



Some people think it's the globe that wastes the least energy as heat.

Slide 11

So how can we tell?

Have a think for a few moments

Slide 12

Efficiency

We can work out the percentage of the energy that is converted into useful energy.

To do this, we calculate something known as the ***efficiency*** for the machine.

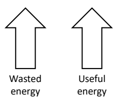
$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 13

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules



$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 14

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules

Wasted energy   Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 15

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules

Wasted energy   Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 16

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules

Wasted energy   Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 17

Remember:
Energy cannot be created or destroyed; it can only be converted from one form into another.

Slide 18

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	64 joules
B	60 joules	24 joules	36 joules
C	80 joules	24 joules	56 joules

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 19

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	64 joules
B	60 joules	24 joules	36 joules
C	80 joules	24 joules	56 joules

Wasted energy

Useful energy

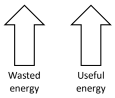
$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 20

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	64 joules
B	60 joules	24 joules	36 joules
C	80 joules	24 joules	56 joules



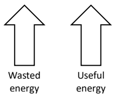
$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 21

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	64 joules
B	60 joules	24 joules	36 joules
C	80 joules	24 joules	56 joules



$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 22

Task 2

4. Problem-solving booklet

Name – Please write in box below

Condition – Please Circle

P	Q

Problem Solving Booklet

This booklet contains some problems to try to solve.

They are set in everyday situations so have a think how you would solve the problem in real life.

You are not expected to solve all of the problems. Just do what you can.

Problem 1 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 joules	12 joules	18 joules
B	15 joules	9 joules	6 joules
C	20 joules	10 joules	10 joules

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

………..

…….

…….

Problem 2 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 joules	15 joules	15 joules
B	20 joules	8 joules	12 joules
C	30 joules	18 joules	12 joules

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

……………

You may use the space below to do any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	80 joules	20 joules
B	150 joules	96 joules	54 joules
C	100 joules	70 joules	30 joules

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

……………

You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	80 joules	64 joules	16 joules
B	75 joules	57 joules	18 joules
C	100 joules	75 joules	25 joules

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

………

………

………

Which is the **least** energy saving light globe?

……………

You may use the space below to do any calculations

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Problem 5 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	60 joules	42 joules	18 joules
B	50 joules	40 joules	10 joules
C	60 joules	54 joules	6 joules
D	50 joules	42 joules	8 joules
E	60 joules	48 joules	12 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 6 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	80 joules	20 joules
B	75 joules	45 joules	30 joules
C	100 joules	90 joules	10 joules
D	100 joules	70 joules	30 joules
E	80 joules	52 joules	28 joules
F	90 joules	63 joules	27 joules

Which is the **most** energy saving globe?

……………

Which is the **least** energy saving globe?

……………

You may use the space below to do any calculations

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Appendix 4
Experiment 4 Materials

1. **Post-test Component 1**

   Similar Questions

Name – Please write in box below

Condition – Please Circle

P	Q

Assessment Component 1

Booklet

20 minutes

Please use a calculator

Problem 2 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 joules	15 joules	
B	30 joules	18 joules	
C	20 joules	8 joules	

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	80 joules	
B	100 joules	70 joules	
C	150 joules	96 joules	

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	75 joules	
B	75 joules	57 joules	
C	80 joules	64 joules	
D	100 joules	74 joules	

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

……………

You may use the space below to do any calculations

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Problem 5 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	50 joules	
B	75 joules	57 joules	
C	100 joules	64 joules	
D	80 joules	74 joules	

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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………

Which is the **least** energy saving light globe?

……………

You may use the space below to do any calculations

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Problem 6 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	60 joules	42 joules	
B	50 joules	42 joules	
C	60 joules	54 joules	
D	50 joules	40 joules	
E	60 joules	48 joules	

Which is the **most** energy saving light globe?

……………

You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

……………

You may use the space below to do any calculations

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Problem 7 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	75 joules	45 joules	
B	80 joules	52 joules	
C	100 joules	80 joules	
D	100 joules	90 joules	
E	100 joules	70 joules	
F	90 joules	63 joules	

Which is the **most** energy saving globe?

……………

Which is the **least** energy saving globe?

……………

You may use the space below to do any calculations

………..

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2. Post-test Component 2

Transfer Questions

Name – Please write in box below

Condition – Please Circle

P	Q

Assessment Component 2

Booklet

10 minutes

Please use a calculator

Problem 1

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Fan	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	150 joules	96 joules	
B	100 joules	80 joules	
C	100 joules	70 joules	

Which is the **most** energy saving fan?

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You may use the space below for any calculations

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Which is the **least** energy saving fan?

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You may use the space below for any calculations

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Problem 2

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Fan	Electrical energy used by the fan per second	Heat and sound energy given out per second	Movement energy given out per second
A	90 joules	45 joules	
B	75 joules	45 joules	
C	100 joules	55 joules	

Which is the **most** energy saving fan?

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You may use the space below for any calculations

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Which is the **least** energy saving fan?

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You may use the space below for any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules		50 joules
B	100 joules		70 joules
C	150 joules		90 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A		65 joules	35 joules
B		64 joules	16 joules
C		57 joules	18 joules
D		70 joules	30 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 5 - Leaf Blower

Electric leaf blowers are noisy. They take in electrical energy and give out heat, sound and kinetic energy. Skye and Ananth look at some information about leaf blowers.

Leaf Blower	Electrical energy used by the leaf blower per second	Heat and sound energy given out by the leaf blower per second
Brand A	200 joules	150 joules
Brand B	200 joules	120 joules

Skye says, “Brand B is the most efficient leaf blower because it gives out the least energy as heat and sound.”

Ananth says, “No, you cannot know which is the most efficient because you don’t know how much useful energy is given out by each leaf blower.”

Who do you agree with? …………………………

Explain why

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3. Explicit instruction slides

Slide 1

Saving Energy

Slide 2

Task 1

Slide 3

Energy

Energy cannot be created or destroyed; it can only be converted from one form into another.

Slide 4

Types of energy

1. Heat energy
2. Light energy
3. Sound energy
4. Electrical energy
5. Movement energy
6. Gravitational Potential Energy
7. Elastic Potential Energy

Heat energy
This flows from warm objects to cooler objects. If you give heat energy to something then it will increase in temperature.

Light energy
This is energy that is transferred from one place to another in the form of light.

Sound energy
This is energy that is transferred from one place to another in the form of sound.

Electrical energy
This is energy that is transferred by an electric current in an electrical circuit.

Kinetic energy
This is the energy that a moving object has.

Gravitational Potential Energy
This is the energy that is stored by holding an object above the ground. We know that energy must be stored because if we let the object fall then it will speed up and so its kinetic energy will increase. In other words, if we let go then energy will be released.

Elastic Potential Energy
This is the energy stored when we stretch something or squash something. We know energy is stored because if we let go then that energy will be released.

Slide 5

joules

Energy is often measured in joules which have the symbol “J”

Slide 6

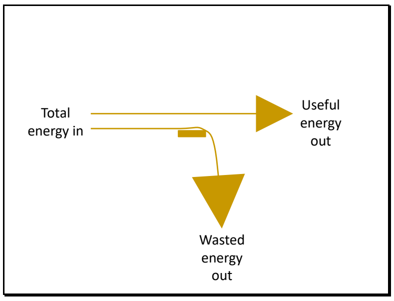
Energy saving light globes

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	
B	60 joules	45 joules	
C	50 joules	28 joules	

Consider this question.

Slide 7



This diagram gives us a way to picture how energy is transformed by machines

Slide 8

So how can we tell?

Have a think for a few moments

Slide 9

Remember:
Energy cannot be created or destroyed; it can only be converted from one form into another.

Slide 10

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	
B	60 joules	45 joules	
C	50 joules	28 joules	

Slide 11

Slide 12

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	
C	50 joules	28 joules	

Slide 13

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	

Slide 14

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules

Slide 15

Efficiency

We can work out the percentage of the energy that is converted into useful energy.

To do this, we calculate something known as the ***efficiency*** for the machine.

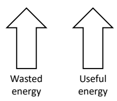
$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 16

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules



$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 17

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 18

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 19

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules	30 joules
B	60 joules	45 joules	15 joules
C	50 joules	28 joules	22 joules

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 20

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	
B	60 joules	24 joules	
C	80 joules	24 joules	

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 21

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	64 joules
B	60 joules	24 joules	36 joules
C	80 joules	24 joules	56 joules

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 22

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	64 joules
B	60 joules	24 joules	36 joules
C	80 joules	24 joules	56 joules

Wasted energy

Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 23

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	64 joules
B	60 joules	24 joules	36 joules
C	80 joules	24 joules	56 joules

Wasted energy　　Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 24

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Heat energy given out by the globe per second	Light energy given out by the globe per second
A	80 joules	16 joules	64 joules
B	60 joules	24 joules	36 joules
C	80 joules	24 joules	56 joules

Wasted energy　　Useful energy

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 25

Task 2

4. Problem-solving booklet

Name – Please write in box below

Condition – Please Circle

P	Q

Problem Solving Booklet

This booklet contains some problems to try to solve.

They are set in everyday situations so have a think how you would solve the problem in real life.

You are not expected to solve all of the problems. Just do what you can.

Problem 1 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 joules	12 joules	
B	15 joules	9 joules	
C	20 joules	10 joules	

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Problem 2 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	30 joules	15 joules	
B	20 joules	8 joules	
C	30 joules	18 joules	

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	80 joules	
B	150 joules	96 joules	
C	100 joules	70 joules	

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	80 joules	64 joules	
B	75 joules	57 joules	
C	100 joules	75 joules	

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 5 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	60 joules	42 joules	
B	50 joules	40 joules	
C	60 joules	54 joules	
D	50 joules	42 joules	
E	60 joules	48 joules	

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 6 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	80 joules	
B	75 joules	45 joules	
C	100 joules	90 joules	
D	100 joules	70 joules	
E	80 joules	52 joules	
F	90 joules	63 joules	

Which is the **most** energy saving globe?

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Which is the **least** energy saving globe?

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You may use the space below to do any calculations

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Appendix 5
Experiment 5 Materials

1. Post-test Component 1

Similar Questions

Name – Please write in box below

Condition – Please Circle

P	Q

Assessment Component 1
Booklet

15 minutes

Please use a calculator

Problem 1 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	20 joules	10 joules
B	15 joules	9 joules
C	30 joules	8 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Problem 2 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	30 joules	15 joules
B	30 joules	12 joules
C	20 joules	12 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	100 joules	20 joules
B	100 joules	38 joules
C	150 joules	54 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	100 joules	16 joules
B	75 joules	18 joules
C	80 joules	24 joules
D	100 joules	26 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 5 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	60 joules	18 joules
B	50 joules	8 joules
C	60 joules	6 joules
D	50 joules	16 joules
E	60 joules	12 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 6 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	75 joules	30 joules
B	80 joules	28 joules
C	100 joules	20 joules
D	100 joules	10 joules
E	100 joules	30 joules
F	90 joules	27 joules

Which is the **most** energy saving globe?

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Which is the **least** energy saving globe?

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You may use the space below to do any calculations

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2. Post-test Component 2

Transfer Questions

Name – Please write in box below

Condition – Please Circle

P	Q

Assessment Component 2
Booklet

10 minutes

Please use a calculator

Problem 1

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Fan	Electrical energy used by the fan per second	Movement energy given out per second
A	150 joules	48 joules
B	100 joules	20 joules
C	100 joules	33 joules

Which is the **most** energy saving fan?

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You may use the space below for any calculations

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Which is the **least** energy saving fan?

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You may use the space below for any calculations

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Problem 2

Electric fans take in electrical energy and give out heat, sound and movement energy (which is also known as 'kinetic energy').

Fan	Electrical energy used by the fan per second	Movement energy given out per second
A	90 joules	45 joules
B	75 joules	30 joules
C	100 joules	45 joules

Which is the **most** energy saving fan?

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You may use the space below for any calculations

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Which is the **least** energy saving fan?

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You may use the space below for any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	50 joules	50 joules
B	100 joules	70 joules	30 joules
C	150 joules	90 joules	60 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	100 joules	65 joules	35 joules
B	80 joules	64 joules	16 joules
C	75 joules	48 joules	27 joules
D	100 joules	70 joules	30 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 5 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Heat energy given out per second	Light energy given out per second
A	50 joules	25 joules	
B	60 joules	30 joules	
C	50 joules	24 joules	
D	60 joules	33 joules	

The last column has not been completed in the table.

Complete the last column using the fact that the total energy given out must equal the total energy used.

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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3. Explicit instruction slides

Slide 1

Saving Energy

Slide 2

Task 1

Slide 3

Energy

Energy cannot be created or destroyed; it can only be converted from one form into another.

Slide 4

Types of energy

1. Heat energy
2. Light energy
3. Sound energy
4. Electrical energy
5. Movement energy
6. Gravitational Potential Energy
7. Elastic Potential Energy

Heat energy

This flows from warm objects to cooler objects. If you give heat energy to something then it will increase in temperature.

Light energy

This is energy that is transferred from one place to another in the form of light.

Sound energy

This is energy that is transferred from one place to another in the form of sound.

Electrical energy

This is energy that is transferred by an electric current in an electrical circuit.

Kinetic energy

This is the energy that a moving object has.

Gravitational Potential Energy

This is the energy that is stored by holding an object above the ground. We know that energy must be stored because if we let the object fall then it will speed up and so its kinetic energy will increase. In other words, if we let go then energy will be released.

Elastic Potential Energy

This is the energy stored when we stretch something or squash something. We know energy is stored because if we let go then that energy will be released.

Slide 5

joules

Energy is often measured in joules which have the symbol "J"

Slide 6

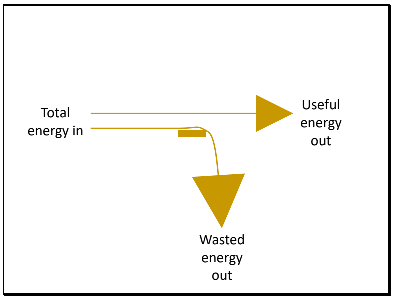
Energy saving light globes

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules
B	60 joules	15 joules
C	50 joules	22 joules

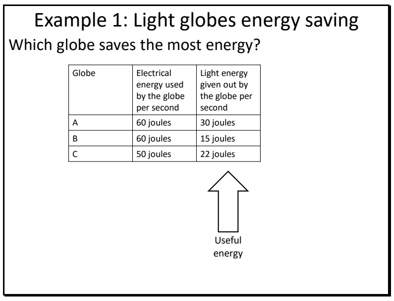
Consider this question.

Slide 7



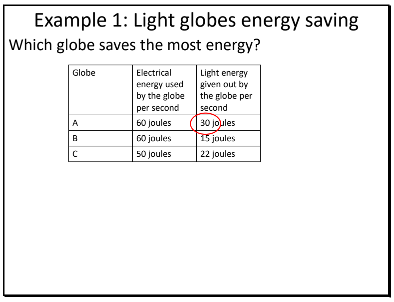
This diagram gives us a way to picture how energy is transformed by machines

Slide 8



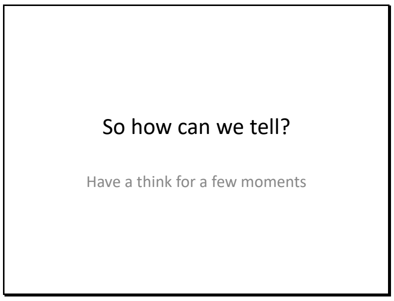
The useful energy given out by light globe is light energy
The wasted energy given out by a light globe is heat energy

Slide 9



Some people think it’s the globe that produces the greatest amount of useful light energy

Slide 10



Slide 11

Efficiency

We can work out the percentage of the energy that is converted into useful energy.

To do this, we calculate something known as the ***efficiency*** for the machine.

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 12

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules
B	60 joules	15 joules
C	50 joules	22 joules

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 13

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules
B	60 joules	15 joules
C	50 joules	22 joules

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 14

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules
B	60 joules	15 joules
C	50 joules	22 joules

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 15

Example 1: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	60 joules	30 joules
B	60 joules	15 joules
C	50 joules	22 joules

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 16

Remember:
Energy cannot be created or destroyed; it can only be converted from one form into another.

Slide 17

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	80 joules	64 joules
B	60 joules	36 joules
C	80 joules	56 joules

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 18

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	80 joules	64 joules
B	60 joules	36 joules
C	80 joules	56 joules

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 19

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	80 joules	64 joules
B	60 joules	36 joules
C	80 joules	56 joules

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 20

Example 2: Light globes energy saving

Which globe saves the most energy?

Globe	Electrical energy used by the globe per second	Light energy given out by the globe per second
A	80 joules	64 joules
B	60 joules	36 joules
C	80 joules	56 joules

$$Efficiency = \frac{useful\ energy\ given\ out}{total\ energy\ taken\ in} \times 100\%$$

Slide 21

Task 2

4. Problem-solving booklet

Name – Please write in box below

Condition – Please Circle

P	Q

Problem Solving Booklet

This booklet contains some problems to try to solve.

They are set in everyday situations so have a think how you would solve the problem in real life.

You are not expected to solve all of the problems. Just do what you can.

Problem 1 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	30 joules	12 joules
B	15 joules	6 joules
C	20 joules	10 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Problem 2 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	30 joules	15 joules
B	20 joules	12 joules
C	30 joules	12 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 3 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	100 joules	20 joules
B	150 joules	54 joules
C	100 joules	38 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 4 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	80 joules	18 joules
B	75 joules	18 joules
C	100 joules	23 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 5 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	60 joules	18 joules
B	50 joules	10 joules
C	60 joules	6 joules
D	50 joules	16 joules
E	60 joules	12 joules

Which is the **most** energy saving light globe?

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You may use the space below to do any calculations

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Which is the **least** energy saving light globe?

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You may use the space below to do any calculations

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Problem 6 – Light globe energy saving

Globe	Electrical energy used by the globe per second	Light energy given out per second
A	100 joules	20 joules
B	75 joules	30 joules
C	100 joules	10 joules
D	100 joules	30 joules
E	80 joules	28 joules
F	90 joules	27 joules

Which is the **most** energy saving globe?

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Which is the **least** energy saving globe?

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You may use the space below to do any calculations

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Appendix 6
Reading Task for Experiments 2-5

1. About the reading task

The reading task was reproduced from tasks available via ReadWorks.org.

Permission to reproduce this task was supplied to the author by email from Wendy Xiao of ReadWorks on 17 July 2021

2. The task

Name – Please write in box below

Condition – Please Circle

P	Q

Reading Task
Booklet

This booklet contains two items to read.

You do not need to finish reading both items.

Why Humans Can't Live Off Sunlight

By ReadWorks

In 2013, a resident of Seattle, Washington, named Naveena Shine decided that she would embark on an experiment. Shine had become fascinated with photosynthesis, the process by which plants are able to make their own food using sunlight. Sunlight contains a significant amount of energy, which plants are able to use to convert water, carbon dioxide, and minerals into oxygen and organic compounds, including nutrients like glucose. Shine reasoned that the human body, if forced to, could do the same thing. So Shine set out to test her hypothesis. In May, she declared that, for the next six months, she would not eat food. Instead, she would limit her diet to only sunlight, water, and tea.

Shine saw her experiment as an important moment in human history, perhaps even a next step in the evolutionary process. On her website, she outlined the many potential advantages of humans being able to produce their own food from sunlight: people would not have to work as hard to earn money to buy food; instead of cooking and shopping, they would have more time to do other things, and many of the earth's natural resources used in the production and preparation of food would be saved for future generations. And why wouldn't it work?

"Plants live on light, and then we eat plants," she concluded. "Are we simply not accessing our inherent ability to live on light?"

Shine also claimed that several people had successfully lived on light before her. She cited a German chemist named Michael Werner, who claims to have eaten no food since 2001, and Ellen Greve, an Australian spiritual leader—known to her followers as Jasmuheen—who said she had not touched a meal since 1993. (These claims were never proven true.) To prove that she was not sneaking food to eat, Shine said she would set up eight video cameras in her trailerto record her every movement. On May 3, 2013, with her predecessors in mind, Shine began her experiment.

The results were dramatic, although perhaps not in the way Shine had planned. Over the next five weeks, Shine lost 30 pounds, dropping from 160 pounds to 130. She felt weak and occasionally had difficulty standing. She reported that when she went outside to get her daily regimen of sun, her hands were cold. Shine predicted that this would be the moment when her body would produce its own food.

“I have the feeling my body has reached a point where it has used up all its stored fats, and is now looking around for what to consume next,” she wrote on Facebook. “I suspect this might be the point where it decides either find and hook into the source where it is able to live on light, or consume the body for sustenance.”

Shine’s experiment received a lot of criticism. Many of her detractors pointed out that, even if her hypothesis was valid, famously cloudy Seattle might not have been the best place to test it out.

On June 19th, after 47 days of the experiment, Shine called it quits. She had lost 33 pounds and was having difficulties holding down water in her stomach. However, Shine did not rule the experiment a failure. Instead, she blamed the early termination on several other, more practical factors, including a lack of funds. Shine had charged the cameras in her trailer to her credit cards. She had expected that visitors to her website would donate funds to pay for the cameras and sustain her experiment. However, after 45 days, she had received only $435, forcing her to leaveher trailer and return to work. She also cited the overwhelmingly negative reaction to her experiment as another reason for its termination.

“From the feedback I am getting,” she wrote, “it is becoming patently clear that most of the world is by no means ready to receive the information I am attempting to produce.”

Shine appears to have escaped from the experiment without permanent damage—although she did sustain a steep drop in her weight and some credit card debt. However, starving yourself can do serious harm to the body and is very dangerous. Others who have attempted the same experiment have not been so lucky. At least four people, inspired by similar teachings about the nutritional value of sunlight, have died from self-inflicted starvation. Starving is dangerous because when the body is deprived of vital nutrients, it begins to shut down some of its vital organs, greatly increasing the chances of illness. If deprivation lasts long enough, then the person can sustain long-lasting injuries or even die.

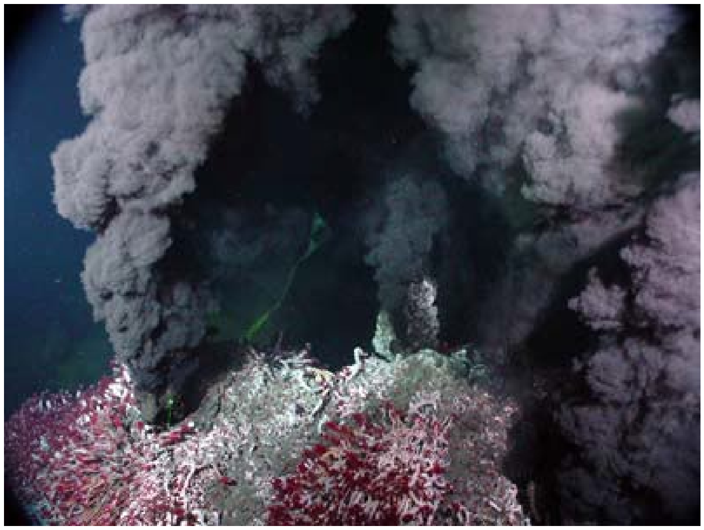
What was Shine’s mistake? Well, she made several. Most importantly, she misunderstood how energy is produced in plants versus how it’s produced in humans. While sunlight does indeed contain energy, only plants are able to render this energy into a usable form. Dr. Ronald Hoffman, a clinician and spokesman about health and nutrition, told the UK’s *Guardian* newspaper that Shine’s ideas were “delusional” and explained her error.

“Plants have what are called chloroplasts that contain chlorophyll, and they have the ability to capture energy from sunlight,” Hoffman said. “Humans don’t have chlorophyll or chloroplasts. No humans do. It is impossible for a human to have that.”

A chloroplast is a structure that is able to produce a very specific chemical reaction in which plants use light energy and carbon dioxide to produce sugars. A chemical reaction is when atoms of one substance are rearranged to make a different substance. During photosynthesis, carbon dioxide atoms the plant draws from the air are split into carbon atoms and oxygen atoms. The carbon atoms are used by the plant to make sugar, a form of carbohydrate. (Carbohydrates are compounds made of carbon, hydrogen, and oxygen.) The plant then discardsany oxygen it does not use as a waste product. This is much like how human beings breathe outcarbon dioxide as a waste product of our own bodily system.

The sugars plants produce during photosynthesis are of a form that plants can use to survive and grow. In this way, the energy that is contained in sunlight is transformed into a different kind of energy. However, the structures capable of making this transformation—chloroplasts—are present only in plants, not humans. When Shine concluded that her experiment would work because plants live on energy from the sun and people eat plants, she was not recognizing that humans do not eat sunlight; people eat the sugars that plants produce. For example, if people eat sweet strawberries, they are not eating the energy from the sun. They are eating a kind of fruit sugar, called fructose, that the strawberry plant produces. If Shine had had a better understanding of photosynthesis and how the human body works, she probably would not have believed her experiment would work.

Life Finds a Way



Deep, deep under the ocean, there is a place unlike anywhere else on Earth. In a place so deep that it's impossible for sunlight to reach it, great rocky tubes shoot up from the sea floor. These tubes, or chimneys, belch out what looks like black smoke, all day and all night. The "smoke" is in fact a mixture of minerals from deep within the earth, which shoot out of the chimneys at extremely hot temperatures. For many years after these things (which scientists now call "hydrothermal vents") were discovered, scientists were sure that nothing could live anywhere near them.

They had lots of reasons to think this. For one, there was absolutely no sunlight. In one way or another, sunlight is the source of almost all life on the surface of earth. Plants use it to make food in a process called photosynthesis, some animals eat those plants, and other animals eat the plant-eaters. Without sunlight, the whole system falls apart, so how could there be any life somewhere that is so deep in the ocean that no light makes it down?

Secondly, the minerals in the smoke, mostly sulfur, were thought for a long time to be poisonous to most living things on Earth. With so much sulfur coming out of the ground at such high temperatures, for many years scientists were pretty confident that nothing could live around these vents.

After studying them for a long time, however, scientists made a shocking discovery. There was life around the vents. Tiny bacteria used the sulfur from the vents to make food – a process called "chemosynthesis." Other animals, like worms and shrimp, then ate this bacteria. A whole ecosystem exists there.

Finding this life made scientists reconsider the power of evolution. They had thought for almost a hundred years that while life was adaptable to a certain extent, there were some things it simply couldn't do without: sunlight and oxygen being two. However, as the animals around the hydrothermal vents proved, life was much more adaptable than they had believed.Now, scientists think that life, just like it does around the vents, could exist right now on Europa, one of Jupiter's moons. Europa has long been known to have vast oceans, but scientists thought that being so far from the sun and having an atmosphere so thin that it can'thold in much air, life would not be possible there. Now, it seems like those factors might not matter as much as previously thought. Some scientists also think that Mars may have once had life on its surface.

As the undersea vents example shows, life is extremely adaptable. All different kinds of places on Earth have animals and plants that have adapted over many years to thrive in the particularplaces where they live. Some animals that live in places where it is very snowy, like high in the mountains or in the arctic, end up white so that they fit in better. Animals and plants that live in the desert, like cacti and camels, have evolved so that they need only the very little water that they get living there. Now think of fish. They are able to swim and breathe perfectly in thewater. But a fish would not do very well living in the middle of the desert. Similarly, if you tooka big black bear from the forest and dropped it down in the middle of the ocean, it would not last long at all.

This is because a process called natural selection has been at work since not long after the earth first formed many billions of years ago. Natural selection allows animals that have traits suited to a particular environment to survive and produce offspring. Animals who are unable to adapt to changes in their environments die off. With this process constantly at work, natureproduces all sorts of animals well-suited to where they are: giraffes with long necks to reach the leaves on the trees in Africa, bears that sleep though long winters where there's no food, and on and on.

The process of natural selection helps us to understand how many plants and animals becamethe way they are. Many times, life finds a way, no matter how harsh the environment.

Appendix 7
Published Paper

Not included in public version of thesis
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https://bit.ly/3AqbhSZ
for access options