Getting the Point: Tracing Worked Examples Enhances Learning

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Author's Declaration

This is to certify that:

I. this thesis comprises only my original work towards the degree of Doctor of Philosophy
II. due acknowledgement has been made in the text to all other material used
III. the thesis does not exceed the word length for this degree.
IV. no part of this work has been used for the award of another degree.
V. this thesis meets the *University of Sydney's Human Research Ethics Committee (HREC) requirements for the conduct of research.*

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Date: 31 March, 2014

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Abstract

Embodied cognition perspectives suggest that pointing and tracing with the index finger may support learning, with basic laboratory research indicating such gestures have considerable effects on information processing in working memory. The present series of experiments examined whether tracing out elements of geometry worked examples could enhance learning through decreased intrinsic cognitive load.

In Experiment 1, 56 Year 6 school students (mean age = 11.20, *SD* = .44) were presented with either tracing or no-tracing instructions on parallel lines relationships. The tracing group solved more acquisition phase practice questions and made fewer errors at the test phase than the non-tracing group, but otherwise test results were limited by ceiling effects. The same materials on parallel lines relationships were used in Experiment 2, but 42 less experienced Year 5 students (mean age = 10.50, *SD* = .51) were recruited to better align the instructional materials with students' knowledge levels. The tracing group outperformed the non-tracing group on a subsequent test and reported lower levels of test difficulty, interpreted as lower levels of intrinsic cognitive load. Experiment 3 recruited 52 Year 6 and Year 7 students (mean age = 12.04, *SD* = .59) presented with materials on angle relationships of a triangle; the tracing effect was replicated on test scores and test errors, but not test difficulty self-reports. Experiment 4 used materials on parallel lines relationships to test hypothesized gradients across experimental conditions with 72 Year 5 students (mean age = 9.94, *SD* = .33), predicting that students who traced on the surface of instructional materials (i.e., affecting visual, kinesthetic and tactile sensory modes) would outperform those who traced in the air above the materials (i.e., affecting visual and

kinesthetic sensory modes), who in turn would outperform those who simply studied worked examples (i.e., affecting visual sensory mode only). The hypothesized gradient was established across practice questions correctly answered, practice question errors, test questions correctly answered, test question time to solution, and test difficulty self-reports.

Taken together, the results of the four experiments establish that incorporating input from the haptic modality into the design of worked example-based instruction enhances the worked example effect generated by cognitive load theory. The results are theoretically and educationally significant in establishing tracing of worked examples as a natural, simple yet effective way to enhance novices' learning of mathematics.

Chapter One: Introduction

There is a long history in educational practice of the use of tracing with fingers to learn. For instance, learning to recognize letters of the alphabet by tracing Sandpaper Letters has been used in Montessori education for over a century (e.g., Montessori, 1914). Inspired by Montessori, the tracing method has been applied to learning other than alphabet letters and its positive effects on learning have been demonstrated across a number of recent experimental studies on letter learning and phoneme identification (e.g., Bara, Gentaz, & Colé, 2007; Bara, Gentaz, Colé, & Sprenger-Charolles, 2004; Hulme, Monk, & Ives, 1987) as well as recognition of geometrical shapes in kindergarten children (e.g., Kalenine, Pinet, & Gentaz, 2011). While the existing studies have repeatedly demonstrated that finger tracing can enhance recognition of visual stimuli, whether such benefits extend to more complex cognitive tasks that require higher levels of abstract thinking and problem solving skills remains to be established.

The present research draws on notions of evolutionary educational psychology (Geary, 2008), embodied cognition perspectives (Glenberg, 2010) and seminal theorizing by educationalists such as Montessori (1912, 1914), to expand the scope of the working memory systems considered by cognitive load theory to those involving haptic information. The fundamental argument underlying the research is that using a pointing finger to trace is a form of biologically primary knowledge that might support the construction of biologically secondary knowledge such as mathematical rules. A series of experiments was conducted to investigate whether explicit instructions to trace out elements of geometry worked examples with the index finger would enhance learning processes and outcomes.

The next chapter of this thesis reviews embodied cognition perspectives, followed by a discussion of utilizing sensorimotor experiences for improving cognition and learning. Studies on the impact of the hands on cognitive processing through their perception, presence and movements are then discussed. The last section of Chapter Two outlines the implications of theories of embodied cognition for mathematics education. Chapter Three reviews cognitive load theory, beginning with a distinction between biologically primary and biologically secondary knowledge (Geary, 2008) followed by a general overview of human cognitive architecture. The three types of cognitive load and the measures to assess cognitive load are then discussed. The following section outlines the five basic principles underlying human cognition and biological evolution by natural selection. Lastly, the final section of Chapter Three discusses the potential use of biologically primary knowledge for the construction of biologically secondary knowledge, and argues on the basis of the literature review that tracing with a finger is a primary skill that can be used during explicit instruction to generate more cognitive resources for secondary knowledge learning. The four experiments conducted to test the tracing hypothesis are presented across Chapter Four to Seven. The results of each experiment provide varying degrees of support for the facilitation of the tracing method during learning processes. Chapter Eight summarizes the major findings of these experiments and then considers the limitations of the present research, concluding with directions for future research.

Chapter Two: Embodied Cognition

2.1 Introduction

Berliner (2006) characterises educational psychology as an enterprise using psychological concepts and methods to understand four "commonplaces of education" (Schwab, 1973): *someone* teaches *something* to *someone else* in *some setting*. Prior to the 1960s, educational psychology was dominated by behaviorism, which focuses on the relationship between instructional manipulation and outcome performance, namely stimulus-response connections (Mayer, 1999). According to this framework, learning is mainly governed by stimulus events and observable responses made in the presence of those events; from a behaviorist perspective, there is no need to speculate about learners' mental mechanisms that might mediate relationships between stimuli and responses (Royer, 2005). Under this paradigm, the main focus of educational psychologists was to determine how instructional manipulations affect behavioral changes (Mayer, 1999).

Inspired in part by the rapid development of electronic information processing and computer technology in the past five decades, a major shift from behaviorist to cognitive perspectives occurred within educational psychology. Unlike the behaviorist approach, the approach of cognitive science is concerned not only with external factors (e.g., instructional manipulations and outcome performance) but also internal factors including cognitive structures and cognitive processing (Mayer, 2005). Since this "cognitive revolution" in the 1960s, educational psychologists have considered how instructional manipulations affect internal cognitive processes and structures (Mayer, 1999).

One of the important contributions of the cognitive revolution is an enhanced understanding of the cognitive architecture underlying learning processes, including the manner in which cognitive structures such as working memory and long-term memory are organized to process information (Mayer, 1999; Sweller, 2012). According to the information processing approach to human cognition, the human mind, like a computer, is a unique information-processing system, divided into three major units—the sensory register, the working memory store, and the long-term memory store (Atkinson & Shiffrin, 1968, 1971). In the middle part of the 20th century, the earlier information-processing view held that learning involves the process of placing new information into long-term memory (Mayer, 2005). Subsequently, in the late 20th century, combining information-processing and constructivist approaches, the cognitive constructivist viewpoint held that learning should involve extracting meaning from the new information and then integrating it with prior knowledge (Phillips, 2000); that is to say, learning is the process of actively constructing knowledge. This view of learners as active processors of information thus changed the focus of instructional design from how to present a stimulus to how to manipulate instructional materials so as to guide and facilitate internal cognitive processes (Driscoll & Burner, 2005).

By the end of 1980s, while the view that the human mind operates as an information processor with relatively little consideration of its connection to the external world still dominated cognitive science, an alternative approach to cognition and learning emerged (Wilson, 2002). Unlike the dominant viewpoint, the new perspective stressed the formative role the environment plays in the development of cognitive capacity and the importance of the human body for interactions with the environment during cognitive processes. Since then, this “embodied” perspective on cognition has rapidly grown and has inspired research theories across a range of disciplines within the behavioral and cognitive sciences.

This current chapter is divided into four parts. The first part discusses the fundamental arguments of the various embodied cognition perspectives. The second part reviews the discussion of sensorimotor experiences by theorists such as Piaget and various ways in which it has been argued sensorimotor experiences might impact upon cognition and education. The third part is focused on the significant role of the hands in gathering sensorimotor experiences, and in promoting cognition and learning. The final part of this chapter discusses how embodied cognition perspectives have informed mathematics education.

2.2 An Embodied View of Cognition

2.2.1 Evolution of human ability. The embodied perspectives on cognition started with the notion of the evolution of human ability. The human brain, for the purpose of enhancing survival and reproduction, required a body for successful interactions with the outside world. A nervous system hence evolved from the need to receive and process input from the environment, as well as to act within and upon the environment (Chiel & Beer, 1997). In this view, the brain is considered as a support system to ensure that the body properly moves around and interacts with the environment, and the body is granted an essential role in constructing the mind. Therefore, the ways people move their bodies influence how they perceive, how they think, and how they remember what they encounter in the environment (Glenberg, 2010; Wilson, 2002). In other words, human cognition is affected by the functions, states, and movements of the body.

2.2.2 Varieties of embodiment. Emerging from the late 1980s, to date, embodiment has become an important principle within cognitive science. Although the basic notion that cognition should be considered as a product of interactions between a body and its surroundings has been generally shared, the concept of embodiment has been formulated in diverse ways (Núñez, Edwards, & Matos, 1999). For instance, approaching from the psycholinguistics perspective, Lakoff and his colleagues (see Lakoff, 1993; Lakoff & Johnson, 1999) found that people often use metaphors derived from bodily experiences to represent or construct abstract conceptual knowledge. One of the examples is that people use the image schema built from physically interacting experiences with containers (i.e., something can be in or out of a container, but not both) to understand the abstract logical concept "either a or b, but not both." The embodiment concept also has been approached from the perspective of language comprehension, which suggests that language understanding often involves bodily action. For example, Glenberg and Kaschak (2002) reported the action-sentence compatibility effect to demonstrate how body movements might interfere with the judgment of sentence meanings. When the direction of the action implied in a sentence (e.g., "Give him a pen", implying action away from the body) matches the direction of the real body movement, sentence comprehension is faster. The phenomenon clearly provides evidence against the traditional view that meaning is derived solely from abstract symbol processing.

Since the general stance that cognition is embodied has been increasingly supported and applied extensively across disciplines within cognitive science, a variety of terms related to the notion of embodiment have been used in the literature, such as *embodied mind* (Lakoff & Johnson, 1999), *embodied intelligence* (Brooks, 1991) and *embodied* *cognitive science* (Clark, 1999). Some researchers (e.g., Semin & Smith, 2002) adopt the term *situated and embodied cognition*, using *situated* and *embodied* interchangeably as if they are equivalent. Some researchers (e.g., Anderson, 2003) argue that the two terms, which stand for two complementary and closely related lines of research, should be separated. The terms that researchers choose, to some extent, reflect their different approaches to embodiment, but the variety of terms and the notions they represent in the literature have the potential to raise a certain degree of confusion about what embodied cognition really means (Wilson, 2002; Ziemke, 2002, 2003).

The diverse terms and notions probably result from the difficulty in treating embodiment as a single viewpoint. To date, there is still no agreement on the fundamentals of embodied cognition, nor a unified theory (Barsalou, 2008). The different approaches to embodiment may share the central stance that human cognition has its roots in interactions between the body and the environment through the perceptual and motor functions of the body (Barsalou, 2008; Wilson, 2002). However, under the banner of embodied cognition, this notion of embodiment has taken different forms. So far, the various claims associated with embodied cognition may be generally divided into three streams.

2.2.3 Main streams of embodied cognition research. The first stream of embodied cognition research stresses that cognition is a sensory-motor activity, so sensorimotor simulation plays an important role in cognition, especially off-line cognition (e.g., Barsalou, 1999; Decety & Grèzes, 2006). It is believed that many cognitive tasks are accomplished by making use of sensorimotor resources, indicating that cognitive processes are body-based. According to this view, the perceptual and motor systems of the human cognitive system apparently have evolved for running off-line cognition—namely, using sensorimotor resources to mentally represent the currently absent information which is needed for a cognitive task (Wilson, 2002). When an interacting experience with an object occurs, the brain will capture the neural activity across modalities underlying the experience as perceptual symbols and integrates them into coherent multimodal representations for the experience. Later, if knowledge related to that previous experience is needed, the multimodal representations will be activated to run a simulation of that experience. The idea of sensorimotor simulations stands in marked contrast to the traditional cognitive science view that treats cognition as the computation on amodal symbols (Barsalou, 1999, 2008).

The second stream stresses that cognition is a situated activity, which occurs from immediate interactions between the body, the environment, and other agents (e.g., Chiel & Beer, 1997; Smith & Semin, 2004, 2007). From this point of view, cognitive processes are continuingly affected by incoming information from the environment and simultaneously keep sending messages to the motor system to execute action in response to the environment. On this account, the cognitive system's core purpose is to support online cognitive tasks in a real-world situation. Such online situated cognition often involves making fast plans to act on the environment under time pressure, so humans have learned to off-load information to the environment and access it when needed in order to manage mental load (Kirsh & Maglio, 1994). Accordingly, rather than mentally storing and manipulating all the available information, the cognitive system uses external resources to support the internal cognitive processing. Wilson (2002) noted that the off-loading strategy does not necessarily need to be deliberate and formalized; instead, it may happen spontaneously and ubiquitously, for example, in the form of co-speech gesture.

The third stream of research considers grounding as the center of cognition (Barsalou, 2008, 2010). The idea of grounding holds that internal cognitive processes need to be connected to concrete referents in the physical world, which has been convincingly demonstrated in language comprehension (e.g., Glenberg & Kaschak, 2002). While most of the previous studies in grounding focused on representations of concrete words, objects and action, recent studies have begun to provide evidence to demonstrate the grounding of abstract concepts, for example, grounding time in the representation of space (Flusberg, Thibodeau, Sternberg, & Glick, 2010). Borghi, Flumini, Cimatti, Marocco, and Scorolli (2011) suggested that even though abstract concepts are not grounded on a single concrete object, they can be grounded on relationships between different objects. It should be noted that the grounded view of cognition particularly emphasizes that cognitive processes can be grounded in many ways such as simulations, situated action and bodily states, and the involvement of the body is not always necessary, which seems to differ from the general idea of "embodied" cognition (Barsalou, 2008, 2010). Some researchers (e.g., Borghi, Scorolli, Caligiore, Baldassarre, & Tummolini, 2013; Pezzulo, Barsalou, Cangelosi, Fischer, McRae, & Spivey, 2011) have recently advocated that notions of embodied cognition and grounded cognition should be explicitly distinguished.

Since the embodied approach to cognition is relatively new, a unified paradigm apparently has not yet been established. However, although the three streams of research within embodied cognition have different foci, they share a common ground that representations of knowledge are connected to sensorimotor interactions with the external world (Holt & Beilock, 2006). Given the increasing evidence that cognitive processes are based in sensorimotor experiences, it can be argued that instructional designers should broaden their focus from a purely cognitive focus to develop a learning environment in which students are allowed to physically manipulate and interact with objects and events. For instance, in the series of experiments of the present research, explicit instructions are added to the paper-based materials, instructing students to use their finger to trace out the information while they are studying the materials. In the next section, the importance of sensorimotor experiences and the benefits of using multimodal input for learning informed by embodied cognition will be discussed.

2.3 Sensorimotor Experiences and Learning

2.3.1 Earlier advocacy of individual sensorimotor experiences. As discussed above, body-environment interactions and sensorimotor experiences as a basis for cognition have been emphasized since the late 1980s, but arguments for the potential of individual experiences to support learning substantially predate the emergence of embodied cognition perspectives. Across the late 19th century and through the early part of the 20th century, John Dewey (1859-1952) developed arguments about the connection between education and personal experiences that education should develop within and for experiences. In *Experience and Education* (1938/1963), he argued that a new form of education should encourage students to gain actual educative experiences and learn through these experiences. Based on these arguments, the challenge for educators is to provide quality experiences, as an educationally worthwhile experience will result in growth, leading students to subsequent experiences. Moreover, educators also need to evaluate the value of an experience based on the interactions that occur between the objective of an experience and students' internal conditions such as personal needs and capacity.

Another example of an "embodied learning" perspective from this period can be found in Jean Piaget's (1896-1980) influential theory of developmental psychology. Piaget (1964) argued that there are four stages for the development of human cognitive abilities, and the first stage, which is from birth to about 2 years old, is termed the "sensorimotor" stage. At this stage, the key ability that babies develop is to build up knowledge about the objects in the surroundings and know how they can be manipulated. Babies will start to use the sensory and motoric functions of their bodies to intentionally try different actions upon and receive responses from the environment. In doing so, "schemes" (using Piaget's terminology) about themselves and the world will gradually develop.

Around the time when embodied cognition perspectives emerged, Paivio (1971, 1986) proposed a dual coding approach to mental representations and highlighted the importance of sensorimotor experiences for facilitating learning in his dual-coding theory. One of the basic premises in the theory holds that mental representations of knowledge keep some concrete qualities of the previous verbal or nonverbal experiences in the real world. Core human cognitive capacity such as language is founded on the nonverbal sensorimotor experiences at a young age, increasingly combined with verbal experiences for the development of a complete dual-coding mind. In other words, the growth of the verbal system depends on a rich nonverbal base. The assumption about the connection between cognition and previous real world experiences is clearly consistent with the viewpoint of embodied cognition (Wilson, 2002).

2.3.2 Multimodal information coding. Taking one step further, Paivio's (1971, 1986) dual-coding theory emphasizes the development of cognition benefits from multiple memory coding. The principle of dual-coding contends that having two independent memory codes to represent a to-be-remembered item will lead to better recall than one single code. Dual codes produce an additive effect, which allows people to create multisensory memory traces to retrieve memory (Paivio, 1986). This notion seems to echo with Barsalou's (1999) theory of perceptual symbols, which are constructed from previous activities involving different sensory systems and are used for running a simulation of action and perception for a later cognitive task.

Based on the dual-coding assumption, research has shown the benefits of multimodal processing for human cognition, though primarily focused on the auditory and the visual modalities. It has been demonstrated that learning in an environment with input from multiple sensory modalities and with interactions between multisensory memories lead to better encoding and retrieving of information (e.g., Lehmann & Murray, 2005; Nyberg, Habib, McIntosh, & Tulving, 2000). Shams and Seitz (2008) argued that the human brain has evolved to learn in a multisensory environment. Therefore, utilizing input integrated across multiple modalities is natural and optimal for learning.

It is undoubted that multimodality is a major aspect of embodied cognition, since cognitive processes based on sensorimotor experiences inevitably involve multiple sensory modalities such as vision, hearing, touch, motor action and so on (Gallese & Lakoff, 2005). In the field of multimodality research, there has been substantial progress in understanding the processing mechanisms of input from the auditory and the visual modalities. So far, relatively less is known about the processing of input from other modalities. Paivio (1986) maintained that information is encoded in two ways—verbal and nonverbal (or imaginal)—and so suggested kinesthetic and tactile inputs may be encoded as a form of image. On the other hand, the recent view of multimodal information processing has argued that there are neural mechanisms within the brain enabling interaction and integration among different sensory systems in concert with task demands (Stein, Meredith, & Wallace, 1994; see also Gallace & Spence, 2009).

Taken together, although it remains unclear if additional memory codings beyond verbal and nonverbal are available, the effectiveness of learning with multiple sensory input has been demonstrated, which is in support of the propositions of embodied cognition. Sensorimotor experiences from concrete interactions with the external world could improve individuals' ability to construct mental models of knowledge. That implies information from multiple sensory modalities would integrate and interact with each other to form a richer multimodal mental representation. Accordingly, in a learning setting, students should be allowed and encouraged to actively and physically interact with the environment. In the following section, gathering sensorimotor experiences from tracing with fingers, object manipulation, body movements, and hand gestures as potential means for enhancing learning and cognition will be discussed.

2.3.3 Utilization of sensorimotor experiences.

Montessori education and the tracing method. Incorporating sensorimotor experiences into learning programs has been a central design principle in Montessori education since the early 20th century. Maria Montessori (1870-1952) believed that body movements and cognition are closely entwined; cognition is embedded in action. Therefore, most of the learning in Montessori classrooms is through physical activities. Students are allowed to freely move around a classroom to acquire physical learning experiences to construct knowledge. For instance, while learning nouns for objects, students are instructed to take the cards with new nouns to find out the corresponding objects and then place the cards beside the objects. While learning new verbs, students are instructed to read verbal commands on Command Cards and then carry out the action. The logic of these activities is that when students have to make a motor response for what they read, they will need to pay more attention to know what a word exactly means. In other words, students' attention will be more effectively directed to the written words and their precise meanings (Lillard, 2005).

Montessori argued for the potentially profound impact of hand movements on human cognition and human society: "The skill of the hands is bound up with the development of mind, and in the light of history we see it connected with the development of civilization…all the changes in environment are brought about by hands" (Montessori, trans. 1967, p. 150-151). Advances in young children's hand movements, such as grasping or pointing, are related to their interest in the physical world, which leads to advances in their cognition (see Fogel, Dedo, & McEwen, 1992; Needham, 2000; Woodward & Guajardo, 2002). Montessori's view on the interdependencies between the development of hand skills and cognition is supported by empirical evidence. For instance, in a study by Needham, Barrett, and Peterman (2002), a group of infants engaged in short play sessions which were designed to enrich their skills of exploring objects by wearing sticky mittens (i.e., mittens with palms that stuck to objects) to pick up toys. It was found that the infants who had this enrichment experience started to pay more visual attention to new objects and used more strategies to explore objects, compared with those infants without such experience.

With Montessori materials, students' hands are constantly in motion. Learning to recognize letters of the alphabet by *Sandpaper Letters* is one of the classical Montessori methods. Students are encouraged to trace sandpaper letters with their fingers in the manner of writing. Besides, while tracing a letter, students simultaneously listen to the sound of the letter pronounced by their teacher (Lillard, 2005; Montessori, 1914). This teaching technique works through a multisensory approach, involving input from several modalities at the same time; students listen to the sound, look at its representation in the form of a letter, and feel the way it is written as they touch and trace the sandpaper letter.

Inspired by Montessori's (1912) idea on tracing letters as an exercise of learning to write before learning to read, educators have used such tracing method in the teaching of children with reading difficulties for a long period. Fernald (1943) demonstrated that asking children with severe reading difficulties to trace around words as if they were writing the words, and say each syllable as it was traced, substantially improved children's reading. It was suggested that tracing could improve memory of retarded readers having difficulty in memorizing spelling patterns and verbal labels, as the tracing movement might produce an additional motor memory trace to link the spoken and written forms of a word (Fernald, 1943; Orton, 1928). However, earlier studies in tracing did not find a positive effect on memory among participants with average or good reading ability (Forster, 1941; Hulme, 1981a; Jensen & King, 1970; Roberts & Coleman, 1958). Hulme and his colleagues have since provided experimental evidence that young normal children could also benefit from the tracing method. Hulme (1979) reported that 8- and 9-year-old children who traced around abstract graphic forms had better visual recognition of the forms in a short-term memory task. Similar results were obtained with alphabet letters and abstract forms in children with reading difficulties and with normal reading capacity. The beneficial effect of tracing on visual recognition of forms was also true of adults (Hulme, 1981b). Later, Hulme et al. (1987) demonstrated that very young children at the age of 3 and 4 also performed better on recalling the names of letters after tracing the letter contours during learning. Furthermore, based on the previous hypothesis that tracing serves as a link between visual and verbal stimuli (e.g., Fernald, 1943; Orton, 1928), Hulme et al. (1987) tested whether tracing could have an effect on verbal retrieval, but this hypothesis was not supported by the results. Accordingly, they maintained that tracing could improve traditional visual-verbal paired-associate learning mainly through its effects on memory for visual recognition.

Hulme (1979, 1981b) speculated that the positive effect of tracing on visual recognition may result from the operation of a separate motor memory system. The motor information encoded while tracing a to-be-remembered form combines with the encoded visual information to improve memory about the form, as presumably visual information and motor information share a common representation in an integrated schema. Perhaps, it could be the spatial information provided by and shared between the visual and the haptic modalities contributes to the improvement of visual recognition (Fredembach, de Boisferon, & Gentaz, 2009).

In summary, although initial arguments about the potential benefits of tracing for learning were relatively vague, this practice seems to be supported by more recent empirical findings. A number of cognitive processes may account for these results. First, such results could be due to multimodal information coding; memorization of words would be increased by multisensory traces. Second, perceptual symbols extracted from a physical activity serve as multimodal traces to facilitate the future knowledge retrieval; thus, when students recall a specific word, their brain will use the perceptual symbols to simulate their previous experience interacting with that word during the tracing activity, such as its visual form, its verbal sound and the sequence of hand movements to write the word. Third, the functional differences of each sensory modality may support a “haptic bond effect” (Fredembach et al., 2009). Due to the fact that visual input is simultaneous and spatial while auditory input is sequential and temporal in nature, young students sometimes encounter difficulties in associating visual forms of words and their corresponding sounds. As the way the hands receive input is both simultaneous and sequential, a haptic bond between visual and auditory inputs may occur. The sequential nature of haptic perception could lead students to explore and process visual forms of words in a thorough and analytical way and so facilitates the association with their sounds (Hatwell, Streri, & Gentaz, 2003; Kalenine et al., 2011). Taken together, it seems reasonable to assume that tracing could serve a bonding function to simultaneously enhance visual and verbal learning.

The benefits of tracing have been established across a number of recent empirical studies on letter learning and phoneme identification (e.g., Bara et al., 2004, 2007) as well as recognition of geometrical shapes in kindergarten children (e.g., Kalenine et al., 2011). Fredembach et al. (2009) extended the positive effect from preschoolers to adults, demonstrating that adding the haptic modality to explore visual stimuli could also help adults to associate signs and their corresponding sounds than simply visual exploration. While the existing studies have repeatedly demonstrated that tracing can enhance recognition of visual stimuli, whether the benefits can extend to more complex cognitive tasks that require higher levels of abstract thinking and problem solving skills has not yet been tested. The series of experiments in this thesis are designed to explore this possibility.

Action-based learning strategy. From an embodiment perspective, language and bodily action are closely related. Indeed, evidence is accumulating that language understanding is based on the automatic and unconscious use of perceptual and motor systems of the body. As mentioned before, the action-sentence compatibility effect reported by Glenberg and Kaschak (2002) showed that sentence understanding involved a simulation of action. Participants in their study judged a sentence as sensible more quickly when the direction implied in that sentence matched the direction of their actual body movement (toward or away from their body). Glenberg and Kaschak (2002) suggested that understanding a “move toward the body” action requires a mental simulation of a “move toward the body” action, and the mental simulation requires activating the same neural systems as planning to make an actual action. Therefore, when the directions of the mentally simulated action and the actual bodily action are different, participants’ sentence comprehension will be hampered. Their argument has been supported by other behavioral studies (e.g., Glenberg, Sato, Cattaneo, Riggio, Palumbo, & Buccino, 2008; Scorolli, Borghi, & Glenberg, 2009; Zwaan & Taylor, 2006) and work in the neurosciences (for a review, see Pulvermüller, 2005).

Based on the embodied view of the close relation between language and action, sensorimotor resources obviously play an essential part in enhancing the comprehension of verbal materials. The embodied approach to language comprehension holds that words and syntax should be grounded in bodily experiences (Glenberg, Goldberg, & Zhu, 2011). According to Bruner (1964), people gradually develop their ability to mentally represent the environment through the course of using enactive, iconic and symbolic modalities. Therefore, for young children, who have fewer experiences to draw on and so often have difficulty creating mental representations using written symbols, providing enactive representations for the target information may bring substantial cognitive benefits (Marley, Levin, & Glenberg, 2010). Likewise, in Piaget's (1964) model of cognitive development, concrete operational experiences have also been highlighted for children aged 7-11 to facilitate their logical thinking. It is believed that action activity brings benefits to children's perception and imagery production (see also Wolff & Levin, 1972). Supported by the previous developmental theories and the recently emerging embodied cognition approach, an activity-based reading intervention, *Moved by Reading*, on the basis of the *indexical hypothesis* (Glenberg, 1997; Glenberg & Kaschak, 2002; Glenberg & Robertson, 1999, 2000) was designed to help children decode written symbols using action-based experiences in memory.

The indexical hypothesis provides an action-based account of reading comprehension. Basically, to understand the meaning of a sentence, three processes are used: (a) indexing (mapping) words to objects in the environment or perceptual symbols (Barsalou, 1999); (b) deriving affordances (i.e., possible interactions between an individual and an object or the environment, Gibson, 1979) from the indexed objects; and (c) using syntax to mesh (integrate) the affordances. Through the three processes, abstract language symbols (i.e., words) are converted into a coherent simulation of action, which is the way the meaning of a sentence will be understood.

According to the indexical hypothesis, reading comprehension requires mapping words and phrases onto concrete experiences or representations of those experiences. During the *Moved by Reading* intervention (Glenberg et al., 2011; Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004), students are provided with appropriate experiences while reading and are then instructed to relate the written symbols to the experiences. The intervention consists of two stages of activities. At the first physical manipulation stage, students are presented sentences describing activities in a particular scenario (e.g., a farm) and a set of toys representing aspects of the scenario (e.g., a barn, animals, farmers). After reading each sentence, students are required to act out the sentence using the toys. The aim of this procedure is to help students map the written words to the corresponding objects and map syntax to action. At the following imagined manipulation stage, after reading a sentence, students are instructed to imagine how they can manipulate the toys to act out the sentence. This procedure is to enable students to create mental images by making use of the physically manipulating experiences from the previous stage.

The efficacy of *Moved by Reading* has been supported by empirical studies in which the instructions of physical and imagined manipulation are applied with variation. Glenberg et al. (2004) demonstrated that young students who received the physical manipulation intervention had a noticeable improvement in comprehension and recall of the text, compared with those in the re-read condition. It was also found that after receiving the training of physical manipulation for a short period, students were able to implement the imagined manipulation strategy while the physical manipulation instruction gradually faded away. The physical external support intervention seems to be a particularly effective method to improve young students' ability to generate mental models while performing text processing tasks. Even when the physical manipulation was executed by other people, young students who simply watched the manipulation had improved reading comprehension (Glenberg, Brown, & Levin, 2007; Marley et al., 2010). Moreover, in the circumstances when real objects are absent, mapping words to the representations of real objects are also sufficient for improving comprehension. Glenberg et al. (2011) found that students who manipulated images on a computer screen performed equally well, or even better, than those who manipulated real objects. This finding may explain why students' comprehension could benefit from the representational gestures that teachers use during instruction.

Although most support for *Moved by Reading* has come from studies in early reading comprehension, it is possible that the benefits of manipulating text-relevant images can extend to older students and adults reading in an unfamiliar domain (Glenberg, 2008, 2010). Ultimately, the *Moved by Reading* intervention is designed to facilitate learning from text, not learning to read (Glenberg et al., 2011). Indeed, it has been demonstrated that the general skill learned from this reading intervention—using experiences to create mental models for text—can be easily transferred to other areas such as story problem solving in mathematics (Glenberg, Jaworski, Rischal, & Levin, 2007) and science exposition of an abstract principle in experimentation (Glenberg, 2008; Richmond, 2008).

Glenberg (2008) argued that the embodied cognition approach to reading comprehension, theoretically speaking, may work more effectively for concrete concepts. As the dual-coding theory suggests, concrete words can be encoded dually, so they are easier to comprehend, compared with abstract words (Sadoski & Paivio, 2004). If so, to enhance comprehension, people need to concretize abstract concepts through encoding them in multiple ways. In doing so, more pathways (e.g., based on both visual and motoric access) to activate mental images of the abstract concepts would be created, resulting in better comprehension. Marley et al. (2010) argued that the benefits of activity-based learning strategies may be explained in two ways. First, an additional motoric code is provided for encoding and retrieving information. The motoric code may further enhance the referential connections, which are used to unite nonverbal and verbal codes, as the dual-coding theory suggests (Paivio, 1971). Second, a self-performed learning activity is labeled and stored as a personal event within episodic memory (Tulving, 1983), which will result in more distinct memory of the target information, compared with a non-self-performed learning task.

In fact, such an action-based learning strategy for verbal materials has been examined by studies on subject-performed tasks, although instead of the embodied aspect of cognition, they put focus on memory for events involving action (Cohen, 1981, 1989; Engelkamp & Zimmer, 1984; Kormi-Nouri, Nyberg, & Nilsson, 1994). The most important finding of studies in this area is that instructing participants to act out, or observe others acting out, the to-be-remembered information during the encoding phase improves later recall (for a review, see Cohen, 1989). Engelkamp and Zimmer (1984, 1985) suggested that the action in subject-performed tasks would be encoded through the motor modality, which then would create an additional motor memory code to improve the original visual and verbal codes. Accordingly, better recall performance should be found in self-performed action than observed action, but their argument was not supported by Cohen (1981, 1983), who found no difference in later recall between self-performed and observed enactment, or Saltz and Donnenwerth-Nolan (1981), who found no difference between self-performed and imagined enactment. However, in subsequent studies, the recall advantage of self-performed over observed action was obtained by Engelkamp and Zimmer (1997) and Hornstein and Mulligan (2001). They argued that the inconsistency between the empirical findings was caused by the study design; the effects of self-performed tasks often occur in within-subject designs, rather than between-subject designs used by Cohen (1981, 1983) and Saltz and Donnenwerth-Nolan (1981).

On the other hand, after failing to obtain an increased effect of dual enactment (i.e., motor encoding and motor retrieval) and only obtaining a limited effect of enactment at retrieval, Kormi-Nouri et al. (1994) suggested that motor processing at encoding and at retrieval may be fundamentally different; otherwise, motor cues should have been effective at recall. They argued that enacted verbal information would be stored as a verbal code, rather than a motoric code, which apparently is at odds with the view of a motor system for storing encoded motor information (e.g., Engelkamp & Zimmer, 1984, 1985). The idea of a distinct motor memory system which could aid visual memory dates back as early as James (1890), who discussed findings of patients who had lost the ability to read because of brain damage beginning to read again by tracing around letters with their fingers (for more reports, see Albert, 1979; Wilson, 1994). These neurological cases were attributed to the existence of a motor memory system. However, although the idea of a motor memory system is long-standing, there is still lack of solid empirical evidence to support its existence. If the system does exist, many questions, such as in what form motor information is encoded and stored or how the motor system collaborates with other memory systems, are still unanswered.

One notable aspect of the research reviewed above is that most of the participants in the studies of subject-performed tasks were university students or mature adults. This may imply that both children and adults could benefit from such action-based learning strategies, just as the *Moved by Reading* intervention suggests (Glenberg, 2008, 2010). Earlier physical experiences with the environment have been recognized as essential sensorimotor foundations for young children to develop language and cognition (Piaget, 1962). However, as children grow up and enter adulthood, their interactions with the environment may become more verbal, but the importance of physical activity does not fade away. While most formal learning mainly relies on verbal language skills, the benefits of physical activity in the acquisition of cognitive skills should not be underestimated, whether for children or adults.

Mindful body movement. Although the importance of bodily action to learning and cognition has been raised, it should be noted that not all kinds of body movements directly lead to changes to knowledge states. Freely moving around may support gathering information from the environment; however, to maximize the chances that learning specifically will be enhanced, physical movements must be carefully designed and guided by teachers. This specific type of body movement, designed to assist learning, is called *mindful movement* (Ben-Ari, 2002; Shoval, 2011). It is differentiated from the body movement which is intended to improve physical capacity and skills, or which occurs in a learning context but does not directly contribute to the learning itself (e.g., forming a circle in order to interact with each other more easily).

To date, there is relatively little research in the role of bodily experiences in the arts, but the advantages of learning and knowing through body movements have been applied to music education. For example, Emile Jaques-Dalcroze (1865-1950) proposed incorporating movements such as rhythmic movements and improvised expression of the heard music through body movements into the musical learning processes. Since then, the Dalcroze approach to music education, known as Dalcroze Eurhythmics, has been used to support musical studies, including music theory, rhythm, instrumental technique, conducting, and performance studies in music, primary and secondary schools (Juntunen & Hyvönen, 2004).

Mindful body movements also have been investigated in the area of cooperative learning. Shoval (2011) found that using mindful movements to assist Year 2 and Year 3 students in geometry class improved their understanding of angles. In addition, she identified three key factors underlying successful mindful movements during the cooperative learning process. The first factor is physical interactions with the environment; it is not only for students to gather information, but also for them to test the correctness of their acquired knowledge through the feedback from the environment (for examples, see Jirsa, 2004; Radford, Demers, Guzman, & Cerulli, 2004). The second factor is demonstration of what students have learned; body movements allow teachers and students to communicate a verbal idea in a physical form, so that teachers can further assess students' internal understanding through their external body movements. Students can also learn from observing others' movements (Deese, Ramsey, Walczyk, & Eddy, 2000). The third factor is sustained active movement activity. Performing physical activities helps students stay active and alert, which also allows teachers to monitor if students are concentrating on learning tasks. Importantly, in order to motivate students to keep on doing and sustain the benefits from movement activity, teachers need to evaluate the learning goals achieved by every activity and make sure of the close connection between activities.

In addition to the three factors, social interaction—a component of successful cooperative learning—is also a key factor contributing to the success of using mindful movements for learning. Most of the studies in cooperative learning have focused on the benefits of verbal communication (see Slavin, Hurley, & Chamberlain, 2003). However, in a cooperative learning group with mindful movement activity, students are allowed to interact through verbal expression as well as body movements. Shoval (2011) found that physical contact with the environment, the use of visual and movement modeling, and socio-kinesthetic interaction were all significant predictors of academic improvement, but the best predictor was sustained movement-aided learning activity. It is worth noting that Shoval (2011) divided social interaction into socio-kinesthetic interaction and socio-verbal interaction, with only socio-kinesthetic interaction being a significant predictor of academic improvement, whereas socio-verbal interaction was not. This finding supports using non-verbal activities for young students who are not capable of engaging in a complex verbal interaction in a cooperative environment (Souvignier & Kronenberger, 2007). Shoval (2011) speculated that in cooperative learning, some subjects such as geometry and physics could be perceived visually and kinesthetically, making verbal interaction of secondary importance. It may be further argued that, with well-designed learning activities, body movements could be sufficient to support learning, with little or no verbal interaction.

Hand gesture. While mindful movement research indicates whole body movements can enhance learning, enhanced learning may also be achieved through hand movements specifically. According to Nathan (2008), one of the ways to see cognition as embodied is through the close relation of gestures to thinking and communication. Indeed, cumulative evidence from a body of research in gesturing has shown that hand gestures, as a small-scale bodily movement, could function as an effective learning tool to facilitate the promotion of cognitive capacity.

As discussed above, simulating previous sensorimotor experiences for off-line cognition is a key proposition in the embodied cognition framework. That is, people activate the same perception and action mechanisms responsible for their previous sensorimotor experiences to create mental images for thinking and speaking (Barsalou, 1999). While doing so, people often gesture. Clearly, gesturing is a common occurrence in human daily life. So far, several researchers (e.g., Goldin-Meadow, 2003; Kita, 2000; McNeill, 1992, 2005) have theorized why people gesture so frequently. From the view of embodied cognition, Hostetter and Alibali (2008, 2010) proposed the *gesture-as-simulated-action* framework to argue that gestures are natural outward expressions of mental simulation, which means gestures emerge from perceptual and motor simulation. According to their arguments, most of the time, sensorimotor simulation occurs covertly; however, when the level of simulating action and perception surpasses the gesture threshold, the simulation will be realized overtly, in the form of gestures. On this account, when people speak or think, gestures are frequently evoked to simulate a previous action or to help imagine an action that can be taken on an object (e.g., imagine the way in which a chair can be moved). Gestures are also evoked to help people mentally manipulate visual images to extract information for constructing thought or speech.

Based on the gesture-as-simulated-action framework, Beilock and Goldin-Meadow (2010; see also Goldin-Meadow & Beilock, 2010) suggested that gestures serve a function to connect action and thought, helping people to ground and express their thinking. Taking this hypothesis one step further, Beilock and Goldin-Meadow (2010) argued that gestures might even have the potential to add information back into the gesturer's mind. They demonstrated that gestures brought action information into gesturers' mental representations, which in turn altered their later thinking and behavior. In their study, participants were required to solve the Tower of Hanoi task twice. After the first solving task, they were asked to explain their solution with gestures. Then, in the second solving task, half of the participants used the original disks, but the disks were switched for the other half (i.e., the smallest disk weighed the most; the largest disk weighted the least). The hypothesis of the study was if the action information added by the gestures during participants' verbal explanation was compatible with the subsequent action they took in the second task, their performance would be improved. If not, their performance would be hampered. It turned out that the switch group spent more time in the second task than the first one, and conversely, the no-switch group spent less time in the second task than the first one. The results suggest that gesturing is not just a natural by-product of people's thinking and speaking; it can bring new information back to change people's thinking.

However, since gestures are representations of action, it might be questioned whether they have more or less effect than action on how people think. To explore the unique influence of gestures on thinking, Goldin-Meadow and Beilock (2010) conducted another study involving solving the Tower of Hanoi problem to investigate the role of gestures versus direct action in the task. This time, after solving the first task, in contrast to the participants in the action group, the gesture group could only use gestures but could not act on the disks while explaining how they solved the problem. It was hypothesized that, during the explanation phase, the gesture group had to generate and hold in mind a detailed internal representation of the disks and the action they took, whereas the action group could off-load some of the information to the environment. Later, when participants were asked to solve the Tower of Hanoi problem for the second round, in which the weights of the disks were adjusted to be at variance with their sizes, participants in the gesture group required more time and more moves to solve the problem. Goldin-Meadow and Beilock (2010) interpreted the results as an indication that gestures linked up action and thinking more directly than actual action on an object, and hence incorporated information into mental representations more strongly than action. This may explain why switching weights of disks hampered the performance of the gesture group more. In short, gestures could more effectively influence people's thinking than action itself.

The findings of gesturing research not only support the theories of embodied cognition but also provide an extended domain in which to investigate the embodied nature of cognitive activity. They also support the idea that gestures could gather advantageous sensorimotor experiences for cognition and learning. More importantly, for some cognitive tasks, gestures may even have a more powerful impact than action sensorimotor experiences. The following sections review scholarship linking gesturing through the hands, information processing, and learning, beginning with a focus on haptic perception, which lays the foundation for the present research to investigate the impacts on learning of incorporating the haptic modality, including and excluding the touch sense, into learning processes.

2.4 The Role of Human Hands in Cognition and Learning

Parallel with the emergence of embodied cognition and the development of information and communication technologies with manual input devices (e.g., touch screens), interest in the role of human hands in cognition and learning has grown rapidly. As knowledge about how the perception, posture and movement of human hands affect information processing has accumulated, people have begun to realize that the hands, with their highly sensitive sense of touch and flexible motor capacity, play a major role in the cognitive activity of daily life (Lederman & Klatzky, 1987).

2.4.1 Haptic perception. *Haptics* refers a perceptual system supported by body movements to extend its perceptual capacity. It enables people to perceive the surroundings through active touch (Klatzky & Lederman, 2003; Lederman & Klatzky, 1987; Loomis & Lederman, 1986). Haptic perception can thus be considered as an active exploration of the environment (Gibson, 1962). The haptic modality has been recognized as the first, the most used and the most reliable modality for people to gather information from interacting with the outside world (Bussell, 2001; Streri, 2003).

As Taylor, Lederman, and Gibson (1973) argued, things that can be touched are more real than things just seen. Haptic feedback from the environment, alongside visual and/or auditory feedback, enhances people’s understanding of objects and events in the external world (Klatzky, Lederman, & Reed, 1987). Alibali and DiRusso (1999) found that when children could touch counted items, they had more accurate performance than pointing to the items or simply looking at them. A touch makes the indication of individual item clearer, so it is easier for children to implement the one-to-one correspondence principle to accomplish a counting task.

The haptic perceptual system is assumed to consist of two subsystems, cutaneous and kinesthetic (Lederman & Klatzky, 2009). According to the terminology of Loomis and Lederman (1986), the cutaneous (tactile) system receives sensory input from receptors embedded in the skin; the kinesthetic system receives sensory input from receptors located within muscles, tendons, and joints; and the haptic system combines all the perception mediated by the cutaneous and kinesthetic systems. According to this account, haptic perception is actually distributed over the whole human body. However, the sensation and the movements of human hands are mostly relied on to feel, to grasp and to manipulate the environment (Sinclair, Kuo, & Burton, 2000). Therefore, research in haptics normally put the focus on the hands and the arms.

Human hands have a highly sensitive sense of touch; the limits of haptic perception, namely discrimination threshold, are normally low. Therefore, human hands can gather a wide range of information about the properties of objects and even can judge a small number of items without counting (Kappers & Tiest, 2013). While visual perception provides global and surface information, the highly functional perception of the hands allows people to obtain detailed information about objects or events. Minogue and Jones (2006) argued that haptic perception has considerable teaching and learning potential, since this system can gather the most direct sensorimotor information to form the foundation for conceptual construction. For example, concrete manipulatives are commonly used by elementary school teachers to teach mathematics, so students can build up their understanding of intangible concepts through direct touch and manipulation (Ross & Kurtz, 1993).

Most of the multimodality research has focused on the auditory and the visual modalities; relatively less research discusses the haptic modality. However, the interest in the haptic modality has begun to be shown in studies of multimodal perception. Recently, based on a theoretical framework drawing on constructivism, working memory research and cognitive load theory (CLT), Chan and Black (2006) proposed a model of multimedia learning enlisting a haptic processor into the cognitive architecture. This model draws on Baddeley's (1992) working memory model and Meyer and Kieras' (1997) executive-process interactive control (EPIC) architecture, suggesting that people receive information for learning via three channels: auditory, visual and haptic. The three types of information enter the brain via ears, eyes, and the sense of touch through hands. Relevant information is then selected and transferred to associated processors—the verbal articulatory loop, the visuo-spatial sketchpad, and the kinematics/tactile display—within working memory for further processing. In an ideal condition, all the three different types of inputs will be integrated to form a stronger mental representation than any one or two. This model may provide a starting point to further examine the effectiveness of incorporating the haptic modality into learning processes.

The increasing interest in the haptic modality has also been shown in research into the interactions between visual perception and haptic perception. Indeed, when using the hands to interact with the environment, both haptic and visual information can be received and transferred to working memory for further processing if the hands are operating within the focus of attention of the visual field. Empirical understanding of how the two types of information and the two modalities influence and interact with each other has progressed rapidly over the past two decades. Research findings in this area have been generating substantial insights into human brain mechanisms and cognitive processes, and will be discussed in the next section.

2.4.2 Hand position. What people see is influenced by where their hands are and what their hands intend to act. A growing body of research suggests that placing the hands around visual stimuli results in profound changes in visual processing of the stimuli in terms of perception, attention and memory. The mechanism underlying this special process is assumed to support specific action intentions (e.g., Bekkering & Neggers, 2002; Fagioli, Hommel, & Schubotz, 2007; Vishton, Stephens, Nelson, Morra, Brunick, & Stevens, 2007; Wohlschläger, 2000). In the field of education, given the accumulating evidence for specialized visual processing of stimuli near the hands, practical applications may be informed for enhancing learning by effectively positioning the hands to interact with visual materials, modulated by goals of learning tasks.

Work in neuroscience has found that the presence of the hands plays an influential role in perception of the environment. In order to support the control of action on objects, humans possess bimodal visuotactile neurons, which specialize in the processing of visual and tactile information in the space near the hands (di Pellegrino, Làdavas, & Farné, 1997; Graziano & Gross, 1993). Such bimodal representations can influence visual attention to the space near the hands, so objects in the perihand area will receive faster recognition and prolonged scrutiny (Abrams, Davoli, Du, Knapp, & Paull, 2008; Reed, Betz, Garza, & Roberts, 2010; Reed, Grubb, & Steele, 2006). Cosman and Vecera (2010) provided further evidence for the influence of hand position on perception and attention, finding that hand position not only would assign the perihand space a processing priority but also allow attention to alter early perceptual processing; thus, objects near the hands will be perceived faster and differently than those farther from the hands. This finding suggests that the hands can act as an efficient cue to segregate target objects from their background.

The altered visual processing near the hands has also been demonstrated when participants display more correct judgment of object sizes (Linkenauger, Ramenzoni, & Proffitt, 2010) and superior change detection (Tseng & Bridgeman, 2011) with their hands appearing near the objects. It is argued that placing the hands near an object often implies an action intention, so the changes in perception would likely arise in order to support the successful execution of an intended action. Accordingly, the vision near the hands will go through a shift from the perception-oriented parvocellular visual pathway to the action-oriented magnocellular visual pathway (Gozli, West, & Pratt, 2012). As the selection-for-action hypothesis (Allport, 1987, 1990) would suggest, the altered perception is mediated by visual attention; people selectively pay attention to information in the environment on the basis of its relevance to an intended action.

The findings of hand-altered perception and attention, which lead to fundamentally different information processes, provide a strong basis for investigating whether memory and the learning of visual materials will be affected by hand position. For instance, an enhancement of attention has been found within the space between the hands, accompanied by a reduction of attention toward the outside of hand space (Davoli & Brockmole 2012). A study by Abrams et al. (2008) found that the shift in attention between items was slower when participants' hands appeared near the display. The slower attentional disengagement would force a thorough evaluation of items. Likewise, Davoli, Brockmole, and Goujon (2012) later reported that hand proximity resulted in a longer processing and a slow rate of learning, suggesting a detail-oriented processing toward objects near the hands. This bias of visual processing toward details may be beneficial for visual discrimination between items with minor differences, as shown in the change detection task by Tseng and Bridgeman (2011). They noted that the increased attention on items near the hands may occur at the expense of a longer attentional shift, but it could allow people to detect rapid onset items faster and encode them into visual working memory deeper, which would result in enhanced visual working memory and improved change detection performance. Interestingly, Davoli, Du, Montana, Garverick, and Abrams (2010) found that the increased focus on visual details would cause impoverished semantic processing involved in reading tasks. Participants' performance in judging the sensibleness of written sentences deteriorated when they put their hands near to the visual display. However, for effective and efficient reading, both spatial processing and semantic processing are needed. Since the proximity of the hands can enhance spatial processing (Abrams et al., 2008; Reed et al., 2006) and form a natural shield of unwanted interference (Davoli & Brockmole, 2012) but with a cost of semantic processing, Davoli et al. (2010) suggested that readers should choose carefully what type of processing would be more important for their current reading text and reading goals.

As the recent research reviewed above has shown, the hands possess the ability to direct the locus of attention; a shift in hand position causes a shift in attention allocation. Importantly, the effect of the hands on attention may not be limited to visual attention. A number of attention studies (e.g., Christ & Abrams, 2006; Mazza, Turatto, Rossi, & Umiltà, 2007; Schreij, Owens, & Theeuwes, 2008) have demonstrated that presenting a peripheral cue in a given sensory modality would lead to a rapid and automatic orientation of attention to the direction of the cue. Moreover, a shift of attention in one sensory modality to a particular location will lead to a corresponding shift of attention in other modalities to the same spatial location (for the cases of audition, vision and touch, see Lloyd, Merat, McGlone, & Spence, 2003; Spence & Driver, 1996; Spence, Pavani, & Driver, 2000). Spence, Nicholls, and Driver (2001) reported that participants in their study found it more difficult to shift their attention away from the tactile modality than from either the auditory or the visual modality. Taken together, it appears that tactile cues, in the form of hand presence, could be a powerful means in capturing attention from different modalities to the space within or near the hands, while also making the important visual information stand out from the surroundings in a learning context.

2.4.3 Hand movement. As mentioned above, haptic perception refers to perception through the hands, which relies on hand movements to actively obtain information in the external environment. For example, a set of hand movements that people use for acquiring specific information about object properties has been identified and described as "exploratory procedures" by Lederman and Klatzky (1987). However, not only do hand movements support the brain by assisting in perceiving the world, but the movements themselves also supply and convey information for the brain. The close relation between hand movements and cognitive processing will be discussed more deeply in the following section.

Definition and taxonomy of gesture. Apparently, people move their hands in a wide variety of ways, for a wide variety of reasons. Hand movements used during speech are often called gestures. *The Oxford English Dictionary* defines gestures as "movements of the body or limbs as an expression of thought or feeling." According to this definition, meaningful hand movements accompanying speech and thinking could be called gestures. In the discussion here, the term "gesture" is used for hand movements accompanying speech. While the speech component is absent, the term "hand movement" is preferably used.

Researchers have proposed a number of taxonomies of gestures (e.g., Efron, 1941; Ekman & Friesen, 1969; Wundt, 1973). Among them, McNeill's (1992) taxonomy is the most widely used in contemporary gesturing studies. This classification of gestures is formulated with essential linkage to speech. It is true that not all hand movements in a learning context are co-speech gestures. However, to date, there is still no prominent classification scheme framed strictly in learning and thinking contexts for hand movements that do not accompany speech. Besides, it could be argued that, in most circumstances, teaching and learning activities in a classroom require social interaction; even thinking and learning by oneself can involve internal monologue. Therefore, most researchers in a domain related to education base their discussions on the taxonomy proposed by McNeill (1992) (Roth, 2001).

McNeill's (1992) classification scheme suggests that gestures can be divided into four types: iconic, metaphoric, deictic, and beat. A gesture is classified as *iconic* if it directly depicts the semantic content of speech. An iconic gesture reveals speakers' memory image and the viewpoint they take toward an object or event. A *metaphoric* gesture is similar to an iconic gesture in that they both depict semantic content, but the image a metaphoric gesture presents refers to a metaphor for an abstract idea. A *deictic* gesture is a pointing movement, with the functions of indicating objects or events in the physical world, or indicating an abstract or non-present referent. A *beat* gesture refers to a simple and non-pictorial movement that does not present a semantic meaning, such as an up-and-down tapping motion.

Based on McNeill's (1992) work, some researchers combine iconic and metaphoric gestures to form a broader category of *representational* gestures (e.g., Alibali & Nathan, 2012; Church, Garber, & Rogalski, 2007). Some researchers even put deictic gestures into this category, based on the phenomenon that people often point to an empty space representing a virtual object or actually point at an object (e.g., Feyereisen & Havard, 1999; Kita, 2000). In this thesis, deictic (pointing) gestures will be separated from representational gestures. The various ways in which pointing can contribute to cognitive processing, other than representing a virtual or an actual object, will be discussed.

It should be noted that gestures may change their forms as their contexts and functions change. As McNeill (1992) observed in one of his case studies, mathematicians used specific gestures for mathematical terms in their conversation. Those mathematical gestures seemed to have distinctive, semi-conventional forms, differing from other narrative gestures. Goldin-Meadow (2003) also suggested that if the manual modality takes on a lot of the communicative burden, namely removing a lot of simultaneous speech, the gestural form ought to be changed (e.g., more language-like). In this sense, it will be difficult to categorize gestures in any fixed way; ideally, gestures would be better understood depending upon their contexts and functions. Recently, McNeill (2005) noted that it is better to see gesture types as gesture dimensions. A given gesture may be simultaneously located on more than one of these dimensions; every gesture has a certain loading of different dimensions.

Flexibility may be one of the reasons why the McNeill taxonomy has been serving as a consensus framework for most research regarding gesturing; it can be adapted for gestures in different discourses (Alibali & Nathan, 2012). For instance, recent studies in mathematics education have begun to identify the gestures specifically used for mathematics learning (see Edwards, 2003). The proposed classification schemes of mathematical gestures are founded on the McNeill taxonomy but with some variations to emphasize the context-specific functions of the gestures in a mathematics talk. For example, iconic-representational gestures, introduced by Arzarello and Robutti (2004), are held to be gestures referring to “a graphic representation of a phenomenon” (p. 307-308).

The attempt to identify mathematical gestures recognizes the importance of contexts in which gestures are used. To some extent, it also shows the usefulness of the McNeill taxonomy as a fundamental framework for researchers to build on their work. Besides mathematical gestures, it is reasonable to believe that more specialized gestures related to different contexts will be explored, such as gestures on direct-touch interactive surfaces.

As gestures are used in various settings, the advantages that gestures can bring to learning and cognitive activity have been discussed from a wide variety of perspectives, ranging from socio-cultural (e.g., Roth, 2001) to cognitive (e.g., Wagner, Nusbaum, & Goldin-Meadow, 2004). The impacts of gesturing on learning reviewed next are broadly divided into two dimensions with a cognitive focus, reflecting the direction of this thesis and its theoretical underpinnings.

Facilitating learning through communication. McNeill (1992) maintained that gestures and speech form a complementary and integrated system; gestures and speech work together to help constitute thought. This argument not only posits that gesturing is an integral part of speech, but also implies that gesturing plays an influential part in thought construction. Indeed, while gesturing, at face value, usually appears like an epiphenomenon of speech, it actually serves a cognitive function for speakers as well as listeners (Iverson & Goldin-Meadow, 1998), and plays a helpful role in cognitive activity such as teaching and learning through facilitating speech and communication (Goldin-Meadow, 1999, 2010).

Conveying information. People often use gestures when they are in a face-to-face conversation. One possibility is because they know that nonverbal behaviors (e.g., facial expression, eye contact, gesture) help to convey feelings to listeners (Friedman, 1979). The view of non-verbal expression, especially gesturing, has been further expanded by recent work. For example, it is found that representational gestures are often produced to convey conceptual information about concrete images or abstract ideas (McNeill, 1992). The imagistic nature of representational gestures allows speakers to add substantial conceptual information to speech and easily to be understood by viewers. Kelly and Church (1998) demonstrated that participants were capable of detecting representational information (e.g., solutions to Piagetian conservation tasks) expressed through gestures, and naturally integrated such information into memory. In their study, both 10-year-old and adult participants displayed the ability to recall information conveyed through the gestures used by the children in a videotape. They picked up the nonverbal information while receiving no instruction to pay attention to the children's gestures. Gestures, apparently, can convey not only affective but also representational information. In this sense, the idea that speakers use gestures for benefiting listeners in terms of speech comprehension is espoused.

Reflecting thinking. On the other hand, information conveyed by a speaker's gestures can also provide insight into the speaker's mind. According to Hostetter and Alibali's (2008) gesture-as-simulated-action framework, gestures—especially representational gestures—are produced when the brain is simulating previous sensorimotor experiences for performing cognitive tasks and the action component of the simulation exceeds a threshold. Representational gestures thus open a window to a gesturer's internal thinking patterns. For educational purposes, this could be a useful way for teachers to assess students' knowledge states.

It has been found that gestures often reflect students' implicit knowledge; that is, things that they already know but they are unaware of or unable to articulate (Perry, Church, & Goldin-Meadow, 1988; Reber & Kotovsky, 1997). The information presented in gestures can reveal gesturers' thinking and normally cannot be found in their speech (Goldin-Meadow, Alibali, & Church, 1993). Church and Goldin-Meadow (1986) found that in a conservation task the strategies students expressed in speech after training actually already appeared in their gestures in the pre-test before training. Roth (2002) also found evidence for the phenomenon that gestures precede the production of speech for expressing ideas. Grade 10 students used gestures to show that they understood new physics principles before they were able to describe the principles verbally (see also Crowder, 1996). Gestures therefore provide an alternative way for students to present the ideas that they have in mind but are not capable of expressing in speech (Goldin-Meadow & Singer, 2003).

In addition to reflecting current knowledge states, students' gestures may also predict the subsequent phase of their learning. Studies have suggested when the thought expressed in students' gestures and that in their speech are discordant, it is often a signal that they are in a transitional knowledge period and about to acquire a new concept (Alibali & Goldin-Meadow, 1993; Church, 1999; Goldin-Meadow, Alibali, et al., 1993). Recently, based on the argument that speech and gestures work together to constitute thought, McNeill (2005) proposed the notion of a *growth point* to argue that when conflicts occur between gestures and speech, it is an opportunity for realignment, which, in turn, leads to learning. When students produce mismatched information in gestures and in speech, it often indicates that different ideas are concurrently activated in their mind. Such students are more likely to improve from the subsequent instructions, if teachers notice the dissonance and tailor instructions to the students' needs (Goldin-Meadow, Nusbaum, Garber, & Church, 1993). In the sense that gestures provide a unique window into a speaker's thought, gestures may carry out a covert "thought" conversation under an overt verbal conversation.

Assisting speech production. If speech-accompanying gestures solely contribute to the understanding between speakers and listeners, speakers will stop gesturing when listeners cannot see them. However, this is not the case. Although the frequency and types of gestures may be affected (Alibali, Heath, & Myers, 2001; Bavelas, Gerwing, Sutton, & Prevost, 2008), speakers, in general, gesture whether they are visible to their audience or not (Alibali et al., 2001; Iverson & Goldin-Meadow, 1998). This phenomenon leads to a possibility that speakers gesture to cognitively benefit themselves in terms of speech production (e.g., Alibali, Kita, & Young, 2000; Rauscher, Krauss, & Chen, 1996).

There are different accounts trying to explain how gestures are involved in producing speech, especially for speech with spatial information. The image-activation account holds that gestures activate and maintain mental images in working memory for lexical search, which is supported by the evidence that participants produce more gestures when describing a spatial image from memory than when the image is visually accessible (de Ruiter, 2000; Wesp, Hesse, Keutmann, & Wheaton, 2001). However, Morsella and Krauss (2004) found that participants also gestured when describing a visually accessible item. Moreover, when spatial images were more difficult to describe verbally, meaning when spatial working memory was taxed, more gestures were produced. These findings led to the conclusion that gestures may aid lexical retrieval, mediated by spatial working memory. The lexicon-access idea was proposed by the lexical access hypothesis (Krauss, 1998; Rauscher et al., 1996). According to this hypothesis, gestures serve as cross-modal primes to facilitate lexical access for a specific image that is gestured. Therefore, people will gesture more when words are more difficult to access. On the other hand, the information packaging hypothesis proposed by Kita (2000) claims that gestures assist in conceptualizing spatial information for speaking. When describing a global image, gesturing helps to decompose the image into small pieces, make decisions about which specific pieces should be mentioned, and organize them into manageable units for the linear verbal system. Therefore, when images are more difficult to be conceptualized into verbalisable forms, people will gesture more (Alibali et al., 2000). Hostetter, Alibali, and Kita (2007) noted that gestures might facilitate speech production at different stages and at different levels, so the different accounts may all stand. One important commonality across these accounts is that gesturing obviously could help to reduce cognitive demands of speech production.

Reducing cognitive load. The visuo-spatial form of gestures make them particularly good at conveying spatial and motor information, so people often use gestures when expressing information that involves images (Alibali, 2005; Hostetter & Alibali, 2008; McNeill, 1992). In other words, gestures may stem from spatial or imagistic representations, and this close relationship may allow gestures to have a direct impact on the cognitive load imposed by producing speech involving spatial information. According to Levelt's (1989) model, there are three stages of speech production: conceptualization, formulation, and articulation. Based on the different accounts for the involvement of gestures in speech production, gestures may work to reduce speakers' cognitive demands across all three stages. Speech production could be a demanding task for the cognitive system, and problems may arise at any of these stages to hinder speaking fluently. Perhaps, producing gestures is a cognitive strategy that the human brain has evolved to adopt automatically in order to deal with the mental demands while having a conversation in a social context (Wilson, 2002). First, gestures may reduce the mental load at the conceptualization stage by activating and sustaining spatial representations in spatial working memory (Wesp et al., 2001), and by organizing thoughts and information for speaking (Hostetter et al., 2007). Second, at the formulation stage, gestures can reduce the load by priming speakers' access to the lexicon for expressing information (Rauscher et al., 1996). Lastly, during speech, gestures help to convey information in a holistic visuo-spatial format in addition to a verbal format, which is linear and segmented, providing speakers a less cognitively demanding way to express information which is difficult to verbalize (Goldin-Meadow, 2003; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001). Aligned with the information packaging hypothesis (Kita, 2000) holding that gestures support speech production by packaging information into verbalisable units, Ping and Golden-Meadow (2010) argued that "gesture can provide an overarching framework that serves to organize ideas conveyed in speech, in effect chunking mental representations to reduce the load on working memory. Gesturing may thus bring a different kind of mental coherence to the representation of an intended message…" (p. 616). In cognitive load theory terms, mechanisms that act to chunk multiple elements of information into a single element are held to reduce intrinsic cognitive load and increase the opportunity for schema construction and/or automation. The series of experiments in the present thesis extend such theorizing, testing if pointing and tracing could enhance learning of ideas conveyed in printed (textual and diagrammatic) instructional materials. More specifically, it is argued that studying information in print with hand movements, compared with simply studying without hand movements, may promote schema construction at the acquisition phase by chunking elements of instructional text and diagrams into a single schema and thus reducing element interactivity, which subsequently facilitates schema retrieval to working memory and schema retention within working memory for solving problems at the test phase, through the mechanism of a decrease in intrinsic cognitive load.

On the other hand, seeing gestures may also reduce gesture-viewers' cognitive load by facilitating speech processing. When listeners have access to both gestures and speech, comprehension is enhanced (Driskell & Radtke, 2003). There may be two ways that gestures can facilitate speech comprehension. One way is through the indexical function of pointing gestures to connect abstract speech and mental ideas to the observable physical world, facilitating the meaning-making process (Glenberg, de Vega, & Graesser, 2008; Glenberg & Robertson, 1999, 2000; Valenzeno, Alibali, & Klatzky, 2003). The other way is through representational gestures that add extra information, namely the visual or imagistic features of speech, to improve gesture-viewers' understanding (McNeill, 1992; McNeil, Alibali, & Evans, 2000). These two reasons may explain why in an instructional setting, teachers frequently use different kinds of gestures to scaffold students' understanding of speech, especially while explaining abstract or complex concepts (Alibali & Nathan, 2007; Church, Ayman-Nolley, & Mahootian, 2004; Roth & Welzel, 2001). With improved comprehension and with less mental effort required for comprehension, students are able to encode new information in a more effective and efficient way, leading to deeper learning. Alternatively, gestures' capacity to reduce mental effort during speech processing may free up students' cognitive resources to learn more and better from instruction. Thus, students given instruction including gestures and speech are more likely to adopt the newly-learned problem solving strategy into their own words and gestures

(Cook & Goldin-Meadow, 2006; Goldin-Meadow, Kim, & Singer, 1999), and even generate their own ideas about the newly-learned information (Ping & Goldin-Meadow, 2008). It is clear that seeing gestures not only lightens the load on working memory but also results in changes to long-term memory (i.e., learning).

Facilitating learning through cognition. While the beneficial impacts of gestures upon teaching and learning have been repeatedly demonstrated through facilitating speech and communication, research has also begun to show that gestures (or hand movements) help to modulate cognition in settings with little or no speech.

Affecting construction of knowledge with instructed gestures. As discussed above, seeing gestures enhances learning from spoken instruction. On the other hand, producing gestures during instruction also brings benefits to learning. Building on the previous finding that gestures reveal implicit knowledge (Goldin-Meadow, Alibali, et al., 1993; Perry et al., 1988), Broaders, Cook, Mitchell, and Goldin-Meadow (2007) demonstrated that students who were asked to freely move their hands while explaining mathematics solutions often found out new strategies and expressed them exclusively in gestures. Accordingly, they suggested that gesturing could be used as a consciously activated skill, albeit one that would run automatically once activated, for extracting implicit knowledge to support explicit learning.

In addition to bringing out existing implicit ideas, instructing students to move their hands also brings in new information to promote the construction of knowledge. Cook, Mitchell, and Goldin-Meadow (2008) found that students who were asked to produce specific hand movements, which displayed a mathematics problem solving strategy during instruction, retained their new learning longer than those who produced no hand movements. Later, Goldin-Meadow, Cook, and Mitchell (2009) suggested that the specific hand movements may help to display and highlight the most important information for students. Students then pick up the information in hand movements and encode it into long-term memory.

Goldin-Meadow et al. (2009) also found that students instructed to use gestures which displayed a correct problem solving strategy had better subsequent test performance than those instructed to use partially correct gestures, who in turn performed better than those instructed to use no gestures. This result is in accordance with the argument of embodied cognition that body movements play a significant part in the meaning-making process (Barsalou, 1999; Glenberg & Kaschak, 2002), which could affect how new knowledge is constructed. Hence, students who produce gestures and no gestures during instruction would learn differently. Students who produce different gestures would construct knowledge differently and thus have different learning outcomes.

Boosting memory retrieval. One of the possible mechanisms by which gesturing plays a role in cognition and learning is through facilitating memory retrieval. When trying to retrieve a word that is temporarily inaccessible, people gesture more often, especially as the target word is high in imageability. Butterworth and Hadar (1989) suggested that the production of iconic gestures would assist retrieving highly imageable words by exploiting the route mediated by visual coding to the words. Not only do the gestures people produce boost verbal memory, but they may also reveal the information that people remember yet are not aware of. As Broaders et al. (2007) suggested, asking students to gesture during their description encourages them to recall and express in gestures the information that is previously captured in a visuo-spatial format, such as shape, size or spatial relationship.

Indeed, for recalling events, the function of gestures as nonverbal memory retrieval cues has been recognized (Ratner, Foley, & McCaskill, 2001). Instructing children to gesture or re-enact is likely to guide their search of memory by reinstating the previously encoded events. For instance, Wesson and Salmon (2001) found that 5- and 8-year-old children's verbal reports of emotionally laden events were enhanced when they were instructed to re-enact their experiences with gestures and bodily action. Stevanoni and Salmon (2005) found that 6- to 7-year-old children in the gesture-instructed condition recalled more correct information two weeks after a learning phase than those in the no-gesture condition. In the case of reacting previous emotional events, Liwag and Stein (1995) argued that nonverbal components associated to an event such as facial expression and action would be activated and then used for retrieving additional information. Similarly, using gestures while recalling a previous event may function as an externalized nonverbal cue and further activate other memory attributes related to that event. Alternatively, using gestures may reduce cognitive demands for verbally reporting an event; cognitive resources are hence allocated to retrieve more information (Stevanoni & Salmon, 2005).

Most of the gesturing studies have focused on how gestures affect memory at recall instead of at encoding. As the benefits of enactment to memory that have been demonstrated by studies in activity-based reading intervention (Glenberg et al., 2004, 2011) and subject-performed tasks (Cohen, 1989; Engelkamp & Zimmer, 1984, 1985, 1994), it could be argued that hand gestures at the encoding phase also contribute to subsequent memory retrieval, functioning like the whole body action does. While learning new words, young children's word retrieval failure has been hypothesized as a result of weak semantic knowledge of that word (McGregor, Friedman, Reilly, & Newman, 2002). In an attempt to enrich semantic knowledge of new object words, Capone and McGregor (2005) provided toddlers with iconic gestures to depict object shapes or functions during instruction. Results showed that providing gestural cues yielded a significant improvement in toddlers' word retrieval and production. Later, Cook, Yip, and Goldin-Meadow (2010) demonstrated that gesturing while encoding action events led to a better performance in immediate and delayed free recall. Gaining insight from previous studies in motoric enactment on memory (e.g., Engelkamp & Zimmer, 1994; Engelkamp, Zimmer, & Biegelmann, 1993; Saltz & Donnenwerth-Nolan, 1981; Von Essen & Nilsson, 2003), Cook et al. (2010) suggested that the additional motor coding may create a robust memory trace, leading to better memory retention. Furthermore, gesturing may be particularly efficient for motoric encoding, as gestures are often produced spontaneously along with speech and thinking but action may not, indicating motoric encoding involved in gesturing will be more spontaneously invoked. Even though sometimes gestures are not spontaneously produced, as in the case of using instructed gestures, the gesturing strategy will operate automatically once it is activated (Broaders et al., 2007). Besides, evidence has shown that instructed gestures can bring benefits to the cognitive system just as spontaneous gestures do (Cook, Yip, & Goldin-Meadow, 2012). Alternatively, it could be that, as Goldin-Meadow (2000) suggested, encoding spatial components of information with the visuo-spatial format of gestures is less cognitively demanding than encoding with a verbal representational format, so more cognitive resources will be available to encode the information more effectively, leading to better subsequent memory recall.

Externalizing working memory. Considering the role of gestures play in speech, communication, learning and cognition, it is reasonable to assume that one of the cognitive mechanisms of gesture production is to help people manage cognitive load, especially while engaged in real-time situated action. For example, having a serious conversation, which requires immediate and continuous responses to feedback from the outside world, could cause a heavy demand for the limited cognitive resources, so people produce gestures to assist in regulating thought and producing speech. Thus, gesturing can be taken as a cognitive strategy to help people manage the working memory "bottleneck" of the cognitive system by reducing cognitive workload.

One possible way for gesturing to help reduce the load on working memory is through externalizing working memory. People often use the "off-loading" cognitive strategy—exploiting external elements in the environment to hold information for working memory—to support cognitive processes (Wilson, 2002). Using *epistemic actions* (i.e., actions taken to make the problem solving procedure simpler; see Kirsh & Maglio, 1994) is one example. This explains why people often physically manipulate objects to solve a problem involving spatial relationships, rather than mentally computing a solution. The off-loading strategy acts to off-load cognitive work to the environment; in other words, recruiting external resources for working memory to accomplish complex cognitive tasks and so to enhance cognitive performance (Cary & Carlson, 2001; Kirsh, 1995; Wilson, 2002).

Considering the embodied nature of cognition, human hands by themselves apparently are one of the external resources, and they may also be a medium to off-load mental processes. People often use the hands to alter the environment or to physically represent some of the information in the external environment to support internal cognitive activity. For instance, Alibali and DiRusso (1999) found that young children counted objects more accurately when gestures were allowed than gestures were prohibited. They argued that keeping track of counted objects and tagging each of the objects physically by using gestures require fewer mental resources than doing visually and mentally by looking at each object. Children would then have more available cognitive resources to recite the number string and assign the number words to the objects, thus enhancing their counting accuracy. Graham (1999) further suggested that gestures might facilitate the implementation of this counting principle by acting as an external representation in two ways. First, as Vygotsky (1962/1986) argued, a concept must be externalized before it can be internalized. Graham (1999) found that participants in her study were able to implement the one-to-one correspondence principle in gestures before in speech. In addition, when the puppet counted for the participants, the participants were more sensitive to the puppet's errors in gestures than in speech. Moreover, older participants used gestures less frequently than young participants. These findings indicated that gestures may serve as an external representation to scaffold children's learning of the one-to-one counting principle until the principle is internalized. Second, gestures may provide an external representation of numerosity, linking number words and counted objects. Through the process of connecting abstract numbers to concrete objects, young children are allowed to build up a concrete understanding of an abstract counting principle.

More recently, Carlson, Avraamides, Cary, and Strasberg (2007) demonstrated that using the hands in simple arithmetic tasks (e.g., array counting and array addition) improved accuracy as well as speed. At each counting step, a temporal coordination between numerical representations to their roles (e.g., as a current total) is needed. The hands are used to support array counting by providing deictic specification to ensure the binding appropriately. Carlson et al. (2007) argued that gestures are especially useful for externalizing working memory, as gestures can be used to represent not only declarative information but also procedural information in support of cognitive tasks (cf. Goldin-Meadow, Nusbaum, et al., 1993).

The literature on counting with the hands discussed above has thus identified pointing as a ubiquitous and spontaneous action used by children and adults to assign number words to the counted objects (Alibali & DiRusso, 1999). Indeed, pointing is a typical strategy that people often use to deal with the limitations of attention and working memory. For instance, when adding a long list of numbers, by pointing a finger to keep the place, attention is directed, and the mental effort required to keep track of the numbers is off-loaded (Kirsh, 1995). Generally, pointing gestures could support cognition in two ways: (a) guiding attention; and (b) grounding mental processes into the physical environment. In doing so, pointing also supports the claims of embodied cognition that cognition is situated and cognitive work can be off-loaded onto the environment (Alibali & Nathan, 2012; Wilson, 2002). For supporting the arguments of this present thesis, the following discussion will focus on pointing gestures more than gestures in general.

Guiding attention. Utilizing pointing gestures to guide attention has been discussed in studies from different areas. For example, in a narrative context, McNeill, Cassell, and Levy (1993) argued that deictic pointing conveys a message that a speaker is orienting or reorienting to an event. More specifically, using deictic pointing helps a speaker to orient, or transport attention and thinking, to the physical reality (i.e., a location in space).

Meanwhile, deictic pointing also guides a listener's attention to follow the shifts of narrative. Deictic pointing thus serves a dual attentional function for both speakers and listeners during narration.

In the research on multisensory learning, it has been argued that the human brain has evolved to learn and operate in a natural environment with information coming from multiple sensory modalities (Shams & Seitz, 2008). However, to enhance such learning, it is imperative to direct attention of multiple senses at once to locate the relevant information for further processing (Mautone & Mayer, 2001). As cognitive load theory (Sweller, 1994, 1999, 2004; Sweller, Ayres, & Kalyuga, 2011) suggests, available cognitive resources should be directed to the main information of instructional materials to reduce unnecessary visual search, avoiding the waste of visuo-spatial resources (Britton, Glynn, Meyer, & Penland, 1982; de Jong, 2010; Loman & Mayer, 1983; Mautone & Mayer, 2001; Sweller, Van Merriënboer, & Paas, 1998). To this end, attentional cues (e.g., color coding, arrows) should be provided to signal students to pay attention on particular information for intentional processing (de Koning, Tabbers, Rikers, & Paas, 2009).

For the purpose of drawing attention, a pointing gesture could serve as a primitive yet effective attention-guiding cue, as people start using pointing to joint attention and interest as young as 12 months of age (Liszkowski, Brown, Callaghan, Takada, & de Vos, 2012; Liszkowski, Carpenter, Henning, Striano, & Tomasello, 2004). In addition, studies of the interactions between visual attention and hand position also provide strong support for using pointing as an attentional cue. As discussed earlier, putting the hands near an object alters people's visual attention and perception toward that object, so it will stand out from its surroundings (Cosman & Vecera, 2010), and it will be scrutinized longer and deeper (Abrams et al., 2008; Reed et al., 2006, 2010). Considering people use pointing gestures in many meaningful ways from an early age (Liszkowaki et al., 2012), and 12-month-old infants are capable of comprehending the informative function of index-finger pointing more than whole-hand pointing (Liszkowski & Tomasello, 2011), it is reasonable to hypothesize that pointing has a similarly powerful influence on attention as whole-hand proximity. In fact, based on studies in the realm of spatial cognition, pointing-based cueing will be particularly suitable for space-based instruction, as pointing at an object leads attention to perceive that object in a more spatially oriented way (Fischer & Hoellen, 2004). Chum, Bekkering, Dodd, and Pratt (2007) found that encoding spatial arrays with pointing movements toward the visual display led to better memory performance. They suggested that pointing makes the feature of spatial arrangement more salient and hence improves the encoding of the arrays (cf. Dodd & Shumborski, 2009).

Taken together, the literature reviewed indicates that pointing may be a highly effective means of managing attention. On the basis of the findings that students learn better when producing gestures themselves than observing gestures (e.g., Goldin-Meadow, Levine, Zinchenko, Yip, Hemani, & Factor, 2012), and the strong effect of the tactile modality on drawing attention (Spence et al., 2001), it could be assumed that making an active pointing movement including touching instructional materials will be an even more powerful attentional cue. Furthermore, as recent experimental research has shown that the combination of multisensory cues may capture spatial attention more effectively than unimodal cues (Spence, 2010), an investigation of the effects on learning of combining a pointing cue with cues in other modalities is clearly warranted.

Grounding cognitive processing. In addition to functioning as an external guide of attention resources, pointing may externalize working memory at a higher level by grounding cognitive processing. More specifically, pointing helps to provide concrete referents of mental representations in the physical world to support cognitive activity, as it is discussed in studies of counting (e.g., Alibali & DiRusso, 1999; Carlson et al., 2007).

Grounding, a key notion in the embodied cognition framework, denotes a mapping process linking abstract symbols or mental representations to something concrete in the physical environment (Glenberg et al., 2008; Glenberg & Robertson, 1999, 2000). It is suggested that grounding could be fulfilled through many ways such as simulation and situated action (Barsalou, 2008). In a language learning context, grounding (or mapping) new words onto objects or action is a frequently used teaching method. Given that representational gestures are derived from simulated action and perception (Hostetter & Alibali, 2008), such grounding could be often accomplished by using representational gestures. For example, McGregor, Rohlfing, Bean, and Marschner (2009) found that while introducing the word *under*, presenting representational gestures in temporal contiguity to externalize the spatial relationships associated with *under* in the visual world reduced students' cognitive demands and increased their understanding of the word.

Like representational gestures, pointing gestures—as they are generally appreciated as an intentional act to indicate something in the physical world—also support the grounding process, but in a different way. Booth, McGregor, and Rohlfing (2008) found that adding pointing to eye-gazing during instruction significantly improved word learning in young children aged 28- to 30-months, compared with using eye-gazing alone. They suggested that the improved performance mainly results from socio-pragmatic factors. As pointing is tightly associated with communicative intent, it may increase children's appreciation of a teacher's intention to name a target object. Moreover, the communicative intent may motivate children to engage more attention to the link between the spoken word and its referent. In other words, pointing could support the grounding process by connecting intangible spoken language to something concrete; it could further promote the grounding with its association with communicative intent.

Taken together, due to its attention-guiding and grounding functions, pointing has been applied to enhancing learning, such as developing literacy skills during the emergent literacy years (i.e., from birth to the end of preschool). It is believed that a well-developed emergent literacy foundation is the key to later literacy advantages (Piasta, Justice, McGinty, & Kaderavek, 2012). One set of precursor skills which has been identified as a central component of emergent literacy development is print knowledge, which refers to knowledge of the specific forms and functions of written language including skills such as print organization and word concept (Justice & Ezell, 2001). To facilitate the development of early print knowledge, providing print referencing by making verbal and nonverbal cues to increase children's attention and contact with print during shared storybook reading has been validated as an effective strategy for learning to read (Evans, Williamson, & Pursoo, 2008; Ezell & Justice, 2000; Justice, Kaderavek, Fan, Sofka, & Hunt, 2009).

According to this strategy, pointing gestures used by adults while reading with children can provide two important types of nonverbal print references. One is tracking the print while reading the text; the other is pointing to the print in text or in illustrations while asking or answering questions, and commenting about the text. Importantly, for print referencing to be effective, the two nonverbal cues have to work in coordination with verbal cues to build up children's understanding of key print concepts. For example, by tracking the print, children's attention is directed to the print while they are listening to the reading by adults, so children learn that the left-to-right directionality of print in English; by pointing to the print while commenting or answering questions about the text, children are guided to attend the connections between spoken words and written words, so they learn that written words are meaningful units to which spoken language can be mapped (Justice & Ezell, 2004; Piasta et al., 2012). Pointing, therefore, plays an essential part in this literacy enhancement strategy, as it provides explicit guidance for young children's exposure to the forms and functions of print, which then leads to the development of print knowledge and advanced literacy skills.

In addition to tasks in language learning and comprehension, many studies in gesturing have chosen mathematics tasks as a testing ground. They provide direct support for the benefits of gesturing for learning; meanwhile, they also indirectly reveal the close relation between gestures and mathematics. Perhaps, while the advantages that gesturing bring to communication and cognition, such as guiding attention and reducing cognitive load, can enhance learning in general, some of the advantages could be particularly beneficial for mathematics learning. In the final section of this chapter, in order to lay the foundation for using mathematics tasks to test the hypotheses of the present research, the relationship between mathematics learning, embodied cognition and hand movements will be briefly discussed.

2.5 Embodied Cognition and Mathematics

One of the basic differences between mathematics and other scientific subjects such as physics or chemistry is that mathematical objects (e.g., numbers), which cannot be directly perceived or observed with instruments, are abstract and accessible by signs (semiotic representations) (Duval, 2006). However, although mathematics can be conceived as an abstract semiotic system, it does not mean that mathematical cognition is beyond the realm of sensation and body motion. As Núñez (2008) has argued, mathematics, perhaps the most abstract conceptual system, is fundamentally grounded in the body, language and human imagination.

2.5.1 Mathematics and hand movements. Many recent views of mathematics education have been developing from the embodied cognition perspectives, highlighting the significance of sensorimotor activities in the process of mathematics teaching and learning (Lakoff & Núñez, 2000). It is reasonable to believe that there is actually a close relation between mathematics and embodied mechanisms, mostly in the form of hand movements and touch (Glenberg, 2008). A good example is counting with fingers, which has been used as one of the basic number learning strategies. Such an embodied strategy is commonly used not only by children but also by adults. A number of studies have shown that number processing involves in the finger motor control system. For instance, by using transcranial magnetic stimulation (TMS), Andres, Seron, and Olivier (2007) demonstrated a specific involvement of finger movements in a counting task. An increase in corticospinal excitability of hand muscle was found while the adult participants were counting dots. In another study by Sato, Cattaneo, Rizzolatti, and Gallese (2007), a visual parity judgment (i.e., odd or even) task was used to examine changes of excitability of hand muscles of adult participants. The major increase in excitability was found on the right hand for smaller numbers (i.e., 1 to 4), indicating that a numerical task, even without a need for counting, also has an effect on the hand motor system. Sato et al. (2007)

suggested that this hand/finger embodied strategy may be developed in childhood and automatically evoked when adults need to represent and manipulate numbers.

2.5.2 Mathematics and bodily experiences. Another way to show that mathematics is embodied is through using linguistic metaphors to build up mathematical understanding. As mentioned earlier, many metaphors people use for speaking and thinking have roots in everyday bodily experiences, which means the construction of mathematical concepts is grounded to some extent in previous physical experiences. For instance, people make use of the common experience of "being physically balanced" to construct the meaning of "balance." The meaning built from the physical experience of being balanced later will serve as a primary means for people to construct abstract understanding of sentences such as "balancing a bank account" (for an extensive discussion, see Johnson, 1987). Likewise, making sense of many obscure mathematical concepts requires the basic bodily experiences in daily life as the initial grounding. An example provided by Lakoff and Núñez (2000) is using conceptual metaphors derived from physical interacting experiences with actual containers (e.g., in, out) to understand abstract mathematical ideas depicted by Venn diagrams.

Analyzing the conceptual system of mathematics from the account of embodied cognition focusing on situated action and social interaction, Núñez et al. (1999) argued that the bodily-grounded nature of cognition provides a foundation for social situatedness. It is through the shared bodily experience that builds up the shared mathematical understanding. For instance, the sensation of balance is one of the basic bodily experiences shared with other human beings in the world. The shared biological and body-based experiences provide a common ground for the shared construction of meanings via social interaction;

as a result, meaning is built up from biological embodied processes within individuals who interact with each other and with the environment in which they exist. Therefore, the mutual understanding of mathematical concepts is socially constructed and situated, on the basis of mutual physical embodied experiences.

2.5.3 Mathematics and multimodal semiotic resources. From the semiotic-cultural perspective on mathematics, mathematical understanding grows with the dynamic practices of semiotic representations (e.g., written words, notations, diagrams, graphs). Students need to re-create, manipulate and interpret multiple mathematical signs in the meaning-making process with their classmates or their teacher. Mathematical knowledge is assumed to be built out of the interplay of various semiotic systems within a collaborative activity (Sáenz-Ludlow & Presmeg, 2006). According to the theory of knowledge objectification (Radford, 2003), students' grasping of mathematical meanings (i.e., to objectify knowledge) is a dynamic social process, which apparently resorts to multiple sensory channels and through various semiotic means of objectification including speech, gesture, bodily action, cultural artifacts and mathematical signs. Radford (2009) found that while discussing a Cartesian graph with others, students frequently used the body and gestures to express and understand abstract mathematical thinking. He suggested that in such a social group, students are offered an opportunity to develop cultural constituted modes of mathematical thinking through their own action and words. Furthermore, as objectification progresses, the configuration of the semiotic means changes, with less bodily action, and more gestures and speech. By using a variety of semiotic resources such as action and gestures in a mathematics classroom, mathematical teaching and learning clearly involve multimodal processing. In this sense, mathematical thinking and understanding is multimodal.

2.5.4 Mathematics and gestures. The embodied cognition and the semiotic-cultural approaches to mathematics seem to have a joint interest in bodily activity, especially gesturing. It may be argued that gesturing is important in a mathematics classroom because it fulfills a crucial function as a nexus bringing together sensorimotor experiences, social communication, semiotic resources and mathematics activity. As Roth (2001) expressed, people make use of three communicative mediums concurrently—language, gestures, and semiotic resources—in the perceptual environment. In a collaborative mathematical reasoning task, Bjuland, Cestari, and Borgersen (2008) found that students frequently used deictic gestures to make connections between two semiotic representations: figures and Cartesian diagrams. In some cases, gestures not only connect various resources together; gestures by themselves are resources as well. Radford (2009) found that while trying to understand a Cartesian graph, students used gestures to specify the borders of perceptual attention and also to provide a kinesthetic expression of ideas such as increase, rest, and decrease. Reynolds and Reeve (2002) also found that during a mathematical conversation, gestures are often used to achieve, maintain and refocus joint attention on the current problem solving, and to reinforce and extend the meaning conveyed by speech. The gestures moving between or within semiotic representations during the problem solving activity are assumed to play a crucial role in provoking reasoning strategies (e.g., comparison, coordination, recapitulation), which are typically helpful in solving mathematics problems (Bjuland et al., 2008).

All in all, the recent work on analyzing the gesture component in mathematics learning contexts provides evidence that gestures play a multi-faceted role in developing mathematical understanding, and that gestures are an important embodied means to support cognitive processes of mathematical knowledge.

2.6 Summary

This chapter aimed to review the field of embodied cognition and its implications for education, with a strong focus on using sensorimotor resources gathered from the hands. The first part of this chapter discussed the central ideas of embodied cognition. The second part discussed the importance of sensorimotor experiences and the ways in which sensorimotor resources could be used for learning. The third part discussed how the hands could contribute to learning and cognitive processing. The final part discussed the relation between embodied cognition and mathematics education.

According to embodied cognition perspectives, hand movements provide sensorimotor resources to facilitate learning and cognitive activity in various ways. Most importantly, hand movements have the potential to facilitate cognitive operations by managing cognitive load, which could bring a significant benefit to the field of instructional design. There is particular potential for cognitive load theory, a contemporary theory of instructional design, to generate new instructional designs by incorporating findings related to embodied cognition, hand movements, pointing and tracing. In the next chapter, the theoretical framework, main principles, and key empirical findings of cognitive load theory are introduced.

Chapter Three: Cognitive Load Theory

3.1 Introduction

Since the 1980s, several learning theories have emerged which foreground key cognitive structures and processes. One of the most prominent cognitively oriented learning theories is Cognitive Load Theory (CLT) (for reviews, see Paas, Renkl, & Sweller, 2003; Paas, Van Gog, & Sweller, 2010; Sweller, 2003, 2011; Sweller et al., 2011). This theory inherited the information-processing view of human cognition and has roots in research on human memory systems and schema theory. It is mainly concerned with the consequences of such research for instructional design, based on the assumption that human cognitive architecture consists of a limited working memory and an unlimited long-term memory. Researchers using this theory investigate a range of variables affecting optimal use of cognitive resources for learning, and have generated a variety of cognitive load effects enhancing the effectiveness and efficiency of instructional materials by enhancing schema construction and automation (Sweller, 2004, 2010a).

Recently, gaining insight from Geary's (Geary, 2002, 2007, 2008) evolutionary educational psychology, the earlier-established theoretical framework of cognitive load theory has incorporated an evolutionary view of human cognitive architecture (Sweller, 2003, 2004). New concepts such as categorization of knowledge, and human cognitive processes related to different categories of information, have been introduced based on the perspective of biological evolution, generating a number of novel implications for instructional design (Sweller, 2008).

The current chapter reviews the development of cognitive load theory, including its theoretical foundations and central ideas. The following part of this chapter is divided into five sections. The first section discusses two categories of knowledge. The second section reviews human cognitive architecture. Then, three types of cognitive load and cognitive load measurement are discussed in the third section. In the fourth section, five cognitive architecture principles derived from the evolved human cognitive architecture, and three cognitive load effects of particular relevance to this thesis, are reviewed. In the final section, a discussion of ways in which biologically primary knowledge might be used to facilitate the acquisition of biologically secondary knowledge is provided.

3.2 Categories of Knowledge

Across the last decade, cognitive load theory has been informed by Geary's (2002, 2007, 2008) evolutionary theory of human cognitive systems, in particular the distinction between biologically primary and biologically secondary categories of knowledge.

3.2.1 Biologically primary knowledge. From an evolutionary viewpoint, knowledge can be divided into two categories—biologically primary knowledge and biologically secondary knowledge—based on its evolutionary status (Paas & Sweller, 2012). In other words, the distinction is made according to the manner in which humans acquire a certain form of information. The evolved human brain is primed to acquire biologically primary knowledge; biologically secondary knowledge, however, is built through formal education and upon the foundation of primary knowledge. Understanding the nature of the two different types of knowledge provides the first step in understanding students' ability and motivation to learn, and may inform teachers about how to design instruction to support students' knowledge acquisition (Geary, 2002, 2007, 2008).

Biologically primary knowledge refers to the information that humans have evolved to acquire by effortless natural processes. No explicit instruction is needed or even available to teach people how to acquire primary knowledge. Geary (2008) argued that this category of knowledge is modular; primary knowledge in different areas may not be closely related and may be acquired separately with different processes at different times in human evolutionary history. Presumably, humans may have evolved to acquire all the necessary primary skills over generations for survival and reproduction in an ever-changing natural environment (Sweller, 2012). Each person, as long as s/he is without major cognitive deficits, is capable of acquiring biologically primary knowledge by simply being immersed in society. For instance, people acquire speaking and listening skills of their native language automatically through interacting with other people, rather than being explicitly taught. Another example comes from the ability to discriminate human faces; it is also one of the primary ability humans have evolved to unconsciously and rapidly acquire. Sweller and Sweller (2006) further suggested that essential human cognitive activity, such as the ability to think, to use general problem solving strategies, and to make decisions and plans, may also belong to the domain of biologically primary knowledge. Importantly, as will be explored in this thesis, the primary knowledge previously stored within long-term memory could be later used to construct biologically secondary knowledge.

3.2.2 Biologically secondary knowledge. Biologically secondary knowledge refers to the information that humans have not yet evolved to acquire in a modular form because such information became culturally important relatively recently (Sweller & Sweller, 2006). Humans may have the capacity to learn mathematics, for example, but have not evolved to acquire specific mathematical concepts by natural processes (e.g., immersion in human society). Likewise, through interpersonal interactions, people can learn to speak and listen to their native language with ease, whereas there is no guarantee that they will learn to read and write in this manner (Sweller et al., 2011).

Humans have an extraordinary ability to create biologically secondary knowledge to cope with variations in the surroundings. The experience-based cultural knowledge, which proves to be useful in social or natural environments, is retained and transferred across generations (e.g., through written records). However, the rate of evolution of human cognitive capacity appears to fall far behind that of cultural knowledge accumulation. It is unlikely for humans to deal with the breadth and complexity of the accumulated cultural knowledge via natural activities. Hence, for people to succeed in modern societies, educational institutions have been invented to facilitate the acquisition of secondary knowledge by providing explicit curricula (Geary, 2008).

The ways to acquire primary and secondary knowledge are obviously different. Most people can automatically learn primary knowledge in an appropriate environment. In contrast, secondary knowledge is not easily assimilated; thus, without direct and carefully organized instructional guidance, very few people can acquire secondary knowledge (Sweller & Sweller, 2006). In addition, from the view of evolutionary educational psychology, the inherent attentional and motivational systems of humans that support primary knowledge learning are not sufficient for secondary knowledge learning. Humans, especially children, have a bias to learning through activities without explicit teaching, such as self-initiated play, exploration, or observation, which suffice for transferring knowledge relevant to get access to the resources needed for survival. Such knowledge is apparently biologically primary. Unfortunately, most of the knowledge and activities (e.g., lectures, standardized testing) provided in modern formal schooling are not what young people prefer to learn and do. This could explain why some children find it difficult to engage in secondary knowledge learning activities, for they are against children's intrinsic motivation (Geary, 2008).

To deal with this difficulty, teachers are advised to provide well-designed guidance to help students transfer from primary to secondary knowledge learning. One way to reach this goal is to build secondary knowledge learning upon the foundation of primary systems. For instance, reading and writing, though belonging to the secondary knowledge learning domain, may actually emerge from people's motivational disposition to communicate with others and influence others' behavior. This means that learning to read and write may share the same motivational systems with learning to speak and listen. In this sense, the motivation underlying learning speaking and listening skills may be used to support learning reading and writing skills, making a learning transition from primary to secondary knowledge domains. Sharing picture books between parents and children is another example of using the mechanisms that support primary knowledge learning to motivate secondary knowledge learning. It is universally common to see parents point to an actual object in the environment and say its name while interacting with their children, which is similar to the way parents use pointing and naming during the parent-child picture book reading. Therefore, sharing picture books with children could provide a natural transition to engage children in a secondary form of knowledge—print, through a primary form of activity (e.g., parental pointing and naming during parent-child interactions) (Geary, 2008).

However, the importance and the necessity of focus and effort for secondary knowledge learning should not be underestimated. Thus, after the transition phase, learning secondary skills will definitely require deliberate instruction. It is risky to assume that students can acquire secondary knowledge in the same natural, effortless way as acquiring primary knowledge. The assumption that school learning can occur effortlessly may lead students to attribute academic failure to lack of ability and thus disengage from schooling (Geary, 2008; Sweller, 2012). Accordingly, rather than assuming that students can construct secondary knowledge naturally by self-exploration, educational institutes should support students' learning with explicit and positively motivating instructional guidance to alleviate learning difficulty and frustration (Sweller, 2012; Sweller et al., 2011).

As mentioned above, primary forms of activities play a helping role in the transition to secondary knowledge learning. In spite of their nature and acquisition being different, secondary knowledge learning actually heavily relies on primary knowledge. It may be difficult or even impossible to acquire secondary knowledge without the assistance of primary knowledge (Sweller, 2012). The primary knowledge that has been acquired will equip humans to acquire and process secondary knowledge. Sweller and Sweller (2006) argued that the mechanisms which humans have evolved to acquire primary knowledge are specific to that category of knowledge. Although humans have not had enough time to evolve such specific mechanisms for secondary knowledge, they do have the capacity to acquire secondary knowledge by imitating the procedures of biological evolution by natural selection. These procedures will be discussed below (see 3.5). Prior to this discussion, human cognitive architecture that is relevant to deal with a variety of information—secondary knowledge in particular—will be reviewed.

3.3 Human Cognitive Architecture

Human cognitive architecture is concerned with the manner in which cognitive structures (e.g., working memory and long-term memory) are organized to process information (Sweller, 2003). It can be referred to the built-in information-processing capacity and mechanisms of the human cognitive system, and to fully exploit human cognitive capacity will require solid understanding of the system (Stillings, Weisler, Chase, Feinstein, Garfield, & Rissland, 1995). In order to generate instructional procedures to facilitate cognitive processes, the characteristics and limitations of human cognitive architecture must be taken into consideration; otherwise, the procedures are unlikely to be effective and efficient (Sweller, 2003, 2004, 2006a).

In understanding the human mind, the "cognitive revolution" in the 1960s contributed a powerful new metaphor. Based on the perspective of information theory (see, for example, Broadbent, 1957; Massaro & Cowan, 1993; Miller, 1956a), the human mind can be understood as analogous to a computer consisting of three major parts to store and manipulate information—the sensory register, the short-term memory store, and the long-term memory store (Atkinson & Shiffrin, 1968). Since the mid-1960s, a variety of information-processing models of human memory systems have developed (e.g., Atkinson & Shiffrin, 1968; Waugh & Norman, 1965). These models may differ in some specific terms, but share the common ground that information entering human memory systems is transformed and stored for later use as it moves through a series of memory stores.

The first memory system of cognitive processes, the sensory register, is assumed to briefly hold information received through humans' five senses (i.e., vision, hearing, touch, smell, and taste). Presumably, there might be a sensory register for each of the five senses, but research has largely focused on the visual and the auditory registers (e.g., Darwin, Turvey, & Crowder, 1972; Sperling, 1960). The information held in the sensory register decays within a few seconds, unless it is attended and assigned meaning for further processing in the next memory system. Since cognitive load theory focuses on the characteristics of working memory and long-term memory, as well as their relation to each other and to cognitive processes, the sensory register will not be further discussed.

3.3.1 Working memory. Working memory (earlier referred to as short-term memory) is considered as a temporary storage area in which information can be kept and manipulated for a short period of time. In the memory model by Atkinson and Shiffrin (1968), it is assumed that this short-term storage, a flexible system for storing and for processing information, could be considered as a 'working-memory' receiving input from the sensory register and the long-term store. It is "a system in which decisions are made, problems are solved and information flow is directed" (Atkinson & Shiffrin, 1971, p. 83). Baddeley (1998) stated that working memory provides a bridge between perception, attention, memory and action. Its function goes beyond passive storage of information, and it is needed for performing complex cognitive tasks such as learning, comprehension and reasoning. Similarly, Logie (1999) compared working memory to the desktop of the brain, for it assists in keeping track of moment-to-moment perception and holding information for making a decision.

Working memory can also be taken as consciousness (Sweller, 1999). Environmental stimuli that pass into a sensory register are not assigned meaning until they are transformed into a code that can be held and hence processed in working memory. In other words, humans are only aware of the information within working memory. To engage in a conscious activity requires that working memory manages all the elements that need processing. For example, to solve a problem, the required elements held and processed in working memory will at least include the start state and the goal state of the problem, and the moves to reduce the differences between the two states. Even though human memory capacity has improved through adaptive processes of evolution, human cognitive architecture still has a highly limited working memory (Stillings et al., 1995).

Constraints in capacity and duration. First of all, working memory is known for its constraint in capacity. Miller (1956b) suggested that only about 7 (±2) chunks (or units, elements) of information can be held in working memory at a time. However, it is noteworthy that although the number of chunks is fixed, their capacity is flexible. A larger chunk can be built by grouping or organizing bits of information together. This implies that working memory, though limited in the number of chunks that can be processed simultaneously, has the potential to hold and manipulate a vast amount of information (Sweller, 2003).

In normal circumstances, working memory is used not only to simply hold but also to process information, including processes such as comparing, combining, relating, remembering, etc. Every conscious cognitive activity requires working memory capacity; therefore, the number of chunks that can be successfully processed simultaneously within working memory may be smaller (Sweller et al., 1998). Cowan (2001, 2010) argued that the capacity of working memory varies across a variety of circumstances, depending on the types of tasks; for instance, whether processing such as rehearsal or grouping is allowed to perform a given task. Nonetheless, in general, the central working memory capacity for young adults is limited to approximately 3 to 5 chunks.

In addition to the limited amount of chunks held, the duration that working memory can hold information is also limited. According to Peterson and Peterson (1959), novel information held within working memory decays rapidly unless it is rehearsed. Without an opportunity for rehearsal, working memory can only hold information for a few seconds. The participants in Peterson and Peterson's (1959) study were provided three letters and three digits (e.g., ABC 309). They were required to repeat the number and then begin counting backwards by 3's from that number (e.g., 309, 306, 303…) until they received a cue to recall the original three letters (e.g., ABC). The result showed that the proportions of correct recall significantly decreased with the increasing recall intervals.

Baddeley's working memory model. Initially, working memory was conceptualized as a unitary short-term memory store (e.g., Atkinson & Shiffrin, 1968). Later, evidence from neuropsychological studies on brain-damaged patients raised difficulties with this notion. Shallice and Warrington (1970) reported a case of a patient with intact long-term memory capacity yet severely impaired digit span especially when using the auditory presentation of items, suggesting a specific defect to his auditory-verbal short-term memory system. After this case, more patients with specific deficits in short-term memory were reported (see Baddeley, 1986). Accordingly, the idea of a 'multi-component working memory system' started to emerge. Recent research has commonly accepted that working memory is a system with multiple processors (e.g., Baddeley, 1992; Baddeley & Hitch, 1974).

The concept of working memory has generated widespread research interest. In the last few decades, the most influential working memory research has been conducted by Baddeley and his colleagues. They built their theoretical framework upon computational modelling, brain imaging techniques and experimental studies with normal participants as well as those who suffered from brain damage (Logie, 1999). Cognitive load theory adopts the working memory model developed by Baddeley and Hitch (1974) to develop propositions. In this model, working memory is viewed as an active, multi-system workplace of the information processing system, consisting of an attentional control system called the central executive which operates in conjunction with two subsystems—the visuo-spatial sketchpad and the phonological loop. This initial framework of working memory has been continuously stimulating further debate and research. Recently, Baddeley (2000; see also Baddeley & Hitch, 2000) added a fourth component, the episodic buffer, into the initial model. The four components are briefly reviewed as follows:

The phonological loop. As a component that is closest to the earlier concept of short-term memory, the phonological loop is the most extensively explored and probably the simplest component of working memory. It is assumed to comprise two subcomponents, a phonological store for holding acoustic or speech-based information for 1 or 2 seconds unless rehearsed, and an articulatory control process, serving a function as subvocalization (i.e., inner speech). Through subvocalization, nameable visually-presented information can be registered into the phonological store (Baddeley, 1992). The utility of the phonological loop for human cognition appears to mainly facilitate language acquisition. Baddeley (1998) assumed that it serves as a language learning device, playing a role both in the language development of children and in the second language learning.

The visuo-spatial sketchpad. Compared with the previous component, the visuo-spatial sketchpad is more complicated and less tractable. It takes charge of holding and manipulating visual and spatial information, as well as visual imagery set up from verbal information (Gathercole & Baddeley, 1993). The original sketchpad model was based on the model of the more-explored phonological loop and they were assumed to share some of the basic characteristics. The sketchpad has been considered as complementary to the phonological loop; however, using visual imagery information is less automatic than phonological information, which often results in heavier demands on the central executive (Baddeley, 1996a). Baddeley (2003) presumed that the sketchpad may play a role in acquiring semantic knowledge about the appearance and the utility of objects, and for spatial orientation; however, further evidence is still needed.

Baddeley (2003, 2012) reflected that research on visuo-spatial working memory is an active but poorly integrated area. Although empirical evidence (see Baddeley, 2003; Logie, 1995; Repovš & Baddeley, 2006; Smith & Jonides, 1997) has supported the distinction between visual and spatial working memory, the models (e.g., the visual cache and the inner scribe proposed by Logie, 1995, 2011) that have been proposed still need further elaboration. In addition, further fractionation of the sketchpad has been explored. Smyth and Pendleton (1989, 1990) found that memory for configured bodily movements (e.g., a ballet position or a gesture) and for spatial tasks involved different processes and hence suggested that a third subsystem for kinesthetic or movement-based information might be included in the sketchpad. Following this idea, Baddeley (2012) speculated that, in addition to visual and spatial subsystems, the sketchpad seems likely to include a haptic channel in charge of kinesthetic and tactile information processing. The information from visual, spatial and haptic sources converges and affects processing in the sketchpad (see Figure 3.1).

The central executive. This component is regarded as a control system of limited attentional capacity as well as a coordinator for the operation of other components within working memory. It is also thought to be responsible for regulating information flow between the subsystems and long-term memory (Gathercole & Baddeley, 1993). The notion of the central executive largely adopted the idea of an attentional controller—supervisory activating system (SAS)—in Norman and Shallice's (1986) model. Baddeley (1996b) mentioned that, in terms of the operation of the central executive, the question of whether it is a cluster of autonomous executive processes (an executive committee), or a unitary coordinated system serving multiple functions (a true executive), still remains. Later, Baddeley (1998) reviewed empirical work and suggested that the executive control system may contain separable executive functions, and it could be fractionated to reveal a number of different executive sub-processes. However, until recently, there is still lack of agreement on the number of its multiple executive functions, or how they collaborate (Baddeley, 2012).

Although the central executive is thought to be the most important component of working memory, the understanding of its capacity and functions has only recently begun and so further exploration has been conducted to modify this understanding (Repovš & Baddeley, 2006). For instance, initially, one hypothetical role of the central executive is to connect working memory with long-term memory (Baddeley, 1996b). Later, the encountered difficulty to account for the assumption has led to the addition of the next component, the episodic buffer.

The episodic buffer. As a subsystem controlled by the central executive and accessed by conscious awareness, the episodic buffer serves as a workspace between the slave systems and long-term memory. It is proposed to be a separate subsystem but also could be considered as the storage of the central executive (Baddeley, 2003). By using multi-dimensional coding, the buffer is able to integrate information from a variety of systems into episodes. However, its capacity of temporary memory storage is limited, depending on the number of chunks it can hold (Baddeley, 2000). As such, the buffer is added to the Baddeley working memory model to solve the binding problem of information from different sources in an attempt to build a coherent representation within working memory (Baddeley & Hitch, 2000).

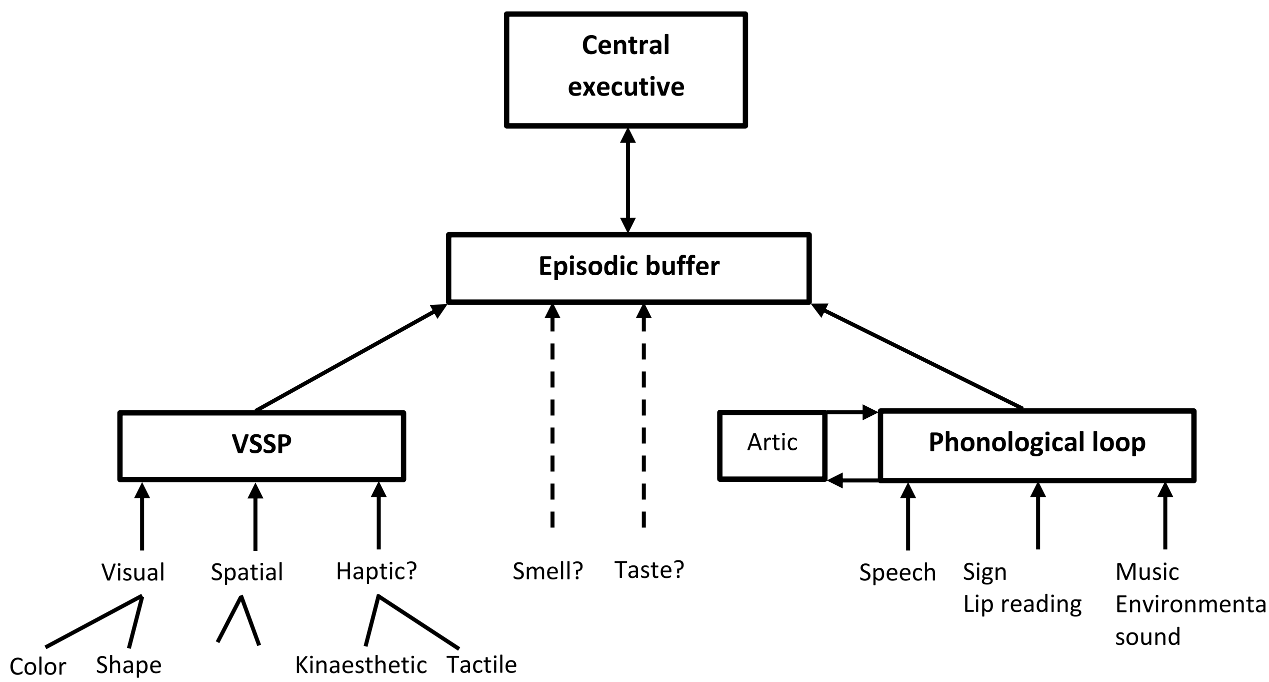

Figure 3.1. A speculative view of the flow of information from perception to working memory. VSSP = visuo-spatial sketchpad. Adapted from “Working memory: Theories, models, and controversies,” by A. Baddeley, 2012, *Annual Review of Psychology*, *63*, p. 23.

3.3.2 Long-term memory. Given the limited capacity of working memory, mechanisms to circumvent the limitations of working memory must be available. Another key aspect of human cognitive architecture, long-term memory, stands in marked contrast to working memory. With no apparent capacity limits to hold learned knowledge in schematic form, long-term memory provides humans with the ability to expand the limited working memory processing capacity (Baddeley, 1986; Paas, Renkl, et al., 2003). The interaction between working memory and long-term memory plays a significant role in performing complex cognitive tasks. It is assumed that knowledge will be permanently stored in long-term memory, albeit humans are not directly aware of the knowledge until it is retrieved into working memory for performing tasks (Cowan, 1988; Sweller, 2003). However, long-term memory should not be taken as a passive store, but rather an integral component of high-level cognitive functioning, and in particular, problem solving.

Characteristics of schemas. The mental structures to organize knowledge like categories within long-term memory are called schemas. Piaget (1952) assumed that a schema is formed from a previous experience and is developed through assimilating and accommodating experiences related to that schema. A previously built schema will keep combining and being modified with new incoming information. According to Rumelhart and Norman (1985), schemas can be considered as models of the outside world, which encode declarative, procedural and conditional knowledge, used to support ongoing perception, understanding, learning, and problem solving. There are two fundamental functions for schemas—one is integrating previous knowledge in a categorized mode and the other is using the built categories to acquire new knowledge.

Moreover, in order to ensure this mechanism operates efficiently, schemas are structured hierarchically (Skemp, 1971). To be more specific, schemas permit multiple elements of information to be classified as one single element according to the manner in which they will be used (Sweller, 1999); lower-order schemas are nested within higher-order schemas. This hierarchical system could allow people to acquire new information related to existing schemas easier and quicker, which implies that it would be more efficient to acquire new knowledge if to-be-learned information is based on prior knowledge (Sweller, 1999, 2003).

As mentioned above, working memory is a crucial intermediate workplace between the sensory register and long-term memory, but with a severe limit in capacity. To circumvent the capacity limitation and to reduce working memory load would heavily rely on using previously stored knowledge structures to organize incoming information. When there is no associated schema existing in long-term memory, there will be a high risk of overburdening working memory, for it has to simultaneously process all the unorganized information. In contrast, when dealing with the information that is associated with existing schemas, working memory is able to process fewer elements (or units) of information at a time by retrieving the associated schemas to combine interacting information into a single element, and so less working memory capacity is occupied (Sweller, 2003).

Schema acquisition and automation. Cognitive load theory holds that learning is a process of constructing new knowledge as schemas into long-term memory (i.e., schema acquisition) and automating the schemas (i.e., schema automation) (Sweller, 1994). Sweller et al. (1998) referred to the characteristics of working memory as determinants of instructional design effectiveness. Learning tasks designed without taking the working memory limitations into consideration can be detrimental to learning (Pawley, Ayres, Cooper, & Sweller, 2005). Well-designed instructional input should not only enhance schema construction by allocating limited cognitive resources toward the activities relevant to learning targets and avoiding overloading each of the processors within working memory, but if possible also support schema automation (Van Merriënboer & Sweller, 2010).

Schema automation refers to the ability to process information without conscious control. With extensive and deliberate practice, stored schemas will be processed with decreasing conscious effort and eventually may be automated without occupying working memory capacity (Sweller, 2003). An automated schema acts like a central executive that can be retrieved unconsciously and directs activity within working memory when no processing is required, so working memory resources are freed up for other tasks (Van Merriënboer & Sweller, 2010). After comparing conscious and automated processing, Shiffrin and Schneider (1977) and Schneider and Shiffrin (1977) suggested that automatic processing should not occupy working memory capacity and cannot be stopped once it starts.

The significance of automation in human cognition not only has been emphasized theoretically, such as in ACT-R theory (see Anderson, 1996, 2005), but also demonstrated experimentally. For instance, through a study on isomorphic versions of the Tower of Hanoi problem, Kotovsky, Hayes, and Simon (1985) demonstrated that students solved problems using automated rules 16 times quicker than when using the rules consciously. Cooper and Sweller (1987) found that having automated schemas could significantly enhance learning outcomes, especially when solving transfer problems of algebra, but it would require extensive learning episodes. Though automation facilitates the performance of cognitive tasks, Van Merriënboer and Sweller (2010) suggested that since building automated schemas takes a great deal of time and effort, perhaps automation of skills that can be transferred across tasks should be developed (e.g., standard procedures to operate equipment or to use software applications).

Schema and expertise. In the development of problem solving expertise, long-term memory plays a particularly important role. Schema theory assumes that possessing a large amount of domain-specific schemas stored in long-term memory is one of the key factors in gaining expertise in a domain (Cooper & Sweller, 1987; Sweller, 1988, 2003; Sweller & Cooper, 1985). In principle, expertise in an area has to be built slowly over many years of deliberate practice, with explicit intention of improving performance (Ericsson, Krampe, & Tesch-Römer, 1993). For example, a chess expert typically requires at least ten years of consistent and continuous practice, and stores tens of thousands of board configurations in long-term memory (Simon & Gilmartin, 1973). In addition, the degree of automation when applying rules to solve problems is another key factor that differentiates the performance between experts and novices (Larkin, McDermott, Simon, & Simon, 1980). A large knowledge base of well-organized domain-specific schemas enables expert problem solvers to rapidly recognize the characteristics of problems and the procedures to solve problems with minimal effort. de Groot (1965) demonstrated that master chess players could reproduce board configurations taken from real games more accurately than amateur players after viewing them for five seconds. Their excellent performance could not be attributed to superior memory, for no reliable difference in the performance between master and amateur players was found when they were asked to reproduce random board configurations. In their area of expertise, chess experts were able to solve problems with ease because they had stored a large number of chess board configurations along with the best moves for each configuration. Thus, when presented realistic board configurations, they perceived the structures and encoded them in chunks, which then led to better recall performance. Similar findings have been obtained in other problem domains such as algebra. Sweller and Cooper (1985) found that students with higher levels of expertise in algebra had better memory recall after briefly seeing algebraic equations, compared with those with lower levels of expertise.

Chase and Simon (1973) later replicated de Groot's (1965) results and found that the recall of both master and amateur chess players was limited by the number of chunks. This finding indicated that the superior performance of master players is due to their ability to build larger chunks, each chunk consisting of pieces of chess positions. Likewise, Chase and Simon (1973) also found that the difference between master and amateur players disappeared when random configurations were used. Apparently, it was rarely possible for chess experts to build schemas for random configurations, so they did not have a remarkable performance for the task which was outside their expertise. In short, levels of expertise would heavily depend on the number and the quality of schemas stored in long-term memory.

To sum up, cognitive load theory holds that learning requires the building of schemas within long-term memory, with schema construction and automation providing learning mechanisms which can reduce working memory load and free working memory capacity for further learning tasks. Bearing in mind the characteristics of human cognitive architecture, cognitive load theory researchers aim to improve instructional resources and activities by manipulating hypothesized sources of cognitive load. In the next section, three sources of cognitive load, and the question of measurement of cognitive load, will be discussed.

3.4 Cognitive Load

Cognitive load is considered to be the load imposed on the cognitive system while performing a cognitive task (Sweller et al., 1998). It can also be defined as the processing of information within working memory, which is required to achieve a learning goal (Hogg, 2006; Kalyuga, 2010). The concept of cognitive load was proposed at the early development stage of cognitive load theory as explanation for the results of studies investigating problem solving's interference with learning. Sweller (1988) argued that conventional problem solving through means-ends analysis may impose a heavy cognitive load, which is consequently ineffective for schema acquisition. Since then, this idea has been substantially elaborated. So far, three types of cognitive load have been identified, including intrinsic, extraneous and germane load, which will be discussed in the following section.

3.4.1 Intrinsic cognitive load. Intrinsic cognitive load is related to the natural complexity of information, which depends on the extent of element interactivity and learner expertise (Van Merriënboer, Kester, & Paas, 2006). Anything to be learned can be placed on a continuum of element interactivity, which is assessed by the number of elements that must be attended to simultaneously within working memory (Sweller, 1994, 2003). When a learning task is high in element interactivity, all the elements and their relations must be processed simultaneously; otherwise, there will not be full understanding. Thus, a high element interactivity task is difficult to understand. Learning such task with full understanding may yield a high intrinsic cognitive load, especially if there are many interacting elements.

In contrast, a task with a lot of elements but low in element interactivity does not impose a high intrinsic cognitive load; elements of such task are not highly associated and so can be learned in a serial manner. Sometimes, in an attempt to reduce high intrinsic cognitive load, learning by rote may occur as a result of treating highly interacting elements as isolated elements and thus processing these elements without considering their relationships (Sweller, 2003).

It used to be assumed that intrinsic cognitive load is fixed by the nature of the given material and the given learner expertise. This type of cognitive load cannot be altered, unless changing the task nature or changing knowledge levels held by students (Sweller, 1994, 2010b; Sweller & Chandler, 1994; Sweller et al., 1998). However, ideas that may reduce intrinsic cognitive load, but without compromising full understanding as the ultimate learning goal, via changing instructional procedures have been proposed (Sweller, 2006c). The first idea concerns the construction of schemas. For students with the same level of knowledge, element interactivity is determined by characteristics of materials. However, if students are capable of incorporating several interacting elements into one single element, the number of element interactions will be decreased. In this case, element interactivity is determined by levels of learner expertise. More experienced students are able to use their stored schemas to group at least some of the elements of incoming information while less experienced students need to attend to all of the elements (Sweller et al., 1998). Thus, when learning the same materials, the number of interacting elements differs for experienced students and inexperienced students. The proposed tactic, similar to schema construction, is to provide students with pre-training on relevant elements before the main stage of instruction takes place. In doing so, novice students—especially those with lower levels of knowledge—will learn more effectively with the needed prior knowledge built beforehand (Clarke, Ayres, & Sweller, 2005; Mayer, Mathias, & Wetzell, 2002; Mayer & Moreno, 2003).

The second idea to manipulate intrinsic cognitive load is a strategy using a two-phase isolated-interacting elements learning approach (Pollock, Chandler, & Sweller, 2002), referred to as "the isolated elements effect" (Blayney, Kalyuga, & Sweller, 2010; Sweller, 2011). By dividing a highly complex learning task into several isolated elements, students are allowed to learn these elements with reduced intrinsic cognitive load, instead of dealing with all the elements simultaneously at the risk of overloading working memory. During the first phase, the interacting elements are presented in isolated form without reference to other elements. Once the isolated elements are sufficiently learned, the instructional material in fully interacting form is presented at the second phase, and then students can learn the relations between the elements (Pollock et al., 2002). The superiority of breaking complex high element interactivity materials into separate smaller units for learning over processing all elements at a time was demonstrated by Gerjets, Scheiter, and Catrambone (2004, 2006). They found that students' learning could be further enhanced by successively learning complex problem solutions of worked examples with lower element interactivity, compared with learning the original worked examples.

Nonetheless, even though complex learning tasks can be modified and simplified by specific instructional procedures, technically speaking, what students really deal with will not be the original tasks anymore. That is to say, the nature of tasks is changed.

Therefore, cognitive load theory could still hold that intrinsic cognitive load is bound to the nature of learning tasks as well as levels of learner expertise, independent of instructional techniques (Kalyuga, 2011).

3.4.2 Extraneous cognitive load. Extraneous cognitive load is a result of inadequate instructional procedures that do not directly contribute to, and may even hamper, learning. When a task is simple and so intrinsic cognitive load is low, decreasing extraneous cognitive load may not be necessary, as the total cognitive load may not exceed working memory capacity. However, when a task is high in element interactivity, eliminating extraneous cognitive load is imperative. Otherwise, the instructional task may fail by imposing a heavy intrinsic load plus a heavy extraneous load and consequently overloading working memory (Sweller & Chandler, 1994). Reducing extraneous cognitive load has been shown to efficiently increase learning and has been a primary concern of cognitive load theory (Van Merriënboer & Ayres, 2005).

As discussed above, element interactivity of information is closely related to intrinsic cognitive load. In some cases, element interactivity also determines extraneous cognitive load, such as when instructional procedures cause students to simultaneously process many interacting elements due to unnecessary instructional activities, or when the inappropriate manner in which information is presented (Sweller, 2010b). Unlike the element interactivity associated with intrinsic cognitive load, which sometimes could be beneficial for learning under some circumstances (i.e., the variability effect—when working memory resources are available, increasing the complexity of a task results in increased learning; Paas & Van Merriënboer, 1994b), the high element interactivity associated with extraneous cognitive load is never beneficial and should be minimized

(Sweller, 2011, 2012). Simply put, if the ultimate learning goal of a task remains the same while element interactivity is reduced, the load is extraneous. On the contrary, if reducing element interactivity requires an altered ultimate learning goal, the load is intrinsic (Beckmann, 2010).

3.4.3 Germane cognitive load. In addition to reducing extraneous cognitive load, cognitive load theory argues that effective instruction should be designed to make optimal use of the freed-up working memory resources at the same time, and so the construct of germane cognitive load was introduced (Sweller et al., 1998).

Germane cognitive load refers to the load associated with additional activities that are intentionally designed to directly contribute to schema construction and automation (Kalyuga, 2010; Paas, Tuovinen, Tabbers, & Van Gerven, 2003; Sweller et al., 1998). Instructional designs theorized to increase the load germane to learning include increasing variability of the to-be-studied worked examples (Paas & Van Merriënboer, 1994b), encouraging students to generate self-explanations to identify underlying principles behind solution steps (Atkinson, Renkl, & Merrill, 2003; Chi, Bassok, Lewis, Reimann, & Glaser, 1989), or imagining performing the demonstrated procedures in worked examples (Cooper, Tindall-Ford, Chandler, & Sweller, 2001; Ginns, Chandler, & Sweller, 2003). An increase in germane cognitive load is considered beneficial for enhancing learning outcomes and for deeper learning, as long as the total cognitive load stays within the limits of working memory.

Recently, arguments (e.g., Kalyuga, 2010, 2011) have been made that the traditional definition of germane cognitive load as a load contributing to learning is indistinguishable from that of intrinsic cognitive load. For instance, while increasing variability of worked examples is suggested as an instructional technique to enhance learning through the generation of germane cognitive load, the enhanced learning could be easily argued as a result of an increase in intrinsic cognitive load. Therefore, it has been suggested that the redundant concept of germane cognitive load should be abandoned to keep cognitive load theory precise. In response to such criticism, Sweller (2010b) restated that, unlike intrinsic or extraneous cognitive load, germane cognitive load is not an independent source of cognitive load; it is associated with the working memory resources allocated to deal with the element interactivity that causes intrinsic cognitive load. More specifically, if the instructional design allows working memory resources to be primarily used to deal with the elements associated with intrinsic cognitive load instead of extraneous cognitive load, germane cognitive load will be maximized. On the contrary, if most working memory resources are required to handle the elements associated with extraneous cognitive load, germane cognitive load will be minimized, as few working memory resources will be available to deal with intrinsic cognitive load. According to this formulation, overall cognitive load is decided by the addition of intrinsic and extraneous cognitive load, and germane cognitive load is complementary to extraneous cognitive load. This redefinition, to some extent, differentiates between intrinsic and germane cognitive load, and re-establishes the essential role of germane cognitive load within the cognitive load theory framework.

To ease the cognitive load imposed on working memory during information processing, cognitive load theory holds that wherever possible, extraneous load should be reduced, intrinsic load managed, and germane load optimized, within the limits of total available working memory capacity. Since for a given task, intrinsic cognitive load is fixed, and reducing extraneous cognitive load would automatically increase germane cognitive load to deal with intrinsic cognitive load, most of the instructional techniques generated by cognitive load theory target extraneous cognitive load. The more extraneous cognitive load is reduced, the more germane load will be induced and hence the more learning will be enhanced (Sweller, 2010a; Van Merriënboer & Sweller, 2010). Instructional designs used in the present thesis use a range of features repeatedly demonstrated to reduce extraneous cognitive load, providing a baseline to test hypotheses regarding the capacity of different hand movements to generate germane cognitive load.

3.4.4 Cognitive load measurement. Since cognitive load theory takes managing cognitive load induced by instruction as a key factor in successful learning, it is of crucial importance to measure cognitive load to provide empirical evidence for the instructional effectiveness of such theoretically derived instructional redesigns. During the early period of cognitive load theory, performance measures (e.g., accuracy, error rate) were heavily relied on for estimating cognitive load (e.g., Sweller, 1988). As cognitive load theory developed, it was later recognized that measures of cognitive load could reveal information that was not inferred by performance-based measures. It was then suggested that combining performance and cognitive load measures could constitute a more reliable estimate of the efficiency of instructional methods (Paas, Tuovinen, et al., 2003; Paas, Van Merriënboer, & Adam, 1994).

However, to determine cognitive load is challenging, for cognitive load is a multidimensional construct, involving complex interrelationships among mental load (i.e., the load imposed by task or environmental demands), mental effort (i.e., the amount of cognitive capacity or resources allocated to accommodate the task demands), and learner performance (Paas & Van Merriënboer, 1994a, 1994b). So far, various methods of measuring cognitive load have been used in cognitive load theory research, but currently there is still no single standardized cognitive load measurement. Until recently, how to effectively measure cognitive load is still a problematic issue for cognitive load theory research (Kirschner, Ayres, & Chandler, 2011).

In general, there are two typically used approaches to assess cognitive load: (a) objective measures (e.g., physiological measures or secondary task method), and (b) subjective rating scales. In cognitive load theory research, the measurement of cognitive load mainly relies on subjective self-reported rating scales. The simplicity of this method is its most obvious benefit; it is easy to implement and analyze, and it is not intrusive. The self-reported rating-scale method is based on the assumption that people can reliably introspect their cognitive process and translate their perceived invested mental effort into a numerical value (Paas, Tuovinen, et al., 2003). Paas et al. (1994) introduced a 9-point subjective rating scale of perceived mental effort, based on two earlier studies by Paas (1992) and Paas and Van Merriënboer (1994b). This rating scale was modified from the perceived task difficulty scale developed by Bratfisch, Borg, and Dornic (1972). In Paas (1992) and Paas and Van Merriënboer (1994b), participants were required to rate the amount of invested mental effort on a 9-point scale ranging from 1 to 9, corresponding to "very, very low mental effort" to "very, very high mental effort." Since then, this subjective rating-scale method has been frequently used for estimation of overall cognitive load, though Paas and Van Merriënboer (1994b) noted that further work would be needed to establish the relationship between perceived mental effort and actual cognitive load. Later, Paas, Tuovinen, et al. (2003) described mental effort as "the aspect of cognitive load that refers to the cognitive capacity that is actually allocated to accommodate the demands imposed by the task; thus, it can be considered to reflect the actual cognitive load" (p. 64).

Within cognitive load theory research, this unidimensional self-rating scale has been used successfully in a large number of studies. However, many variations of the original scale have been administered, such as using 5- or 7-point scales, or asking participants to rate their perceived task difficulty, instead of their perceived mental effort (Van Gog & Paas, 2008). For example, participants in the study by Kalyuga, Chandler, and Sweller (1999) were asked to rate how easy or difficult they found the instruction on a 7-point scale ranging from 1 to 7, corresponding to extremely easy to extremely difficult. In this regard, Van Gog and Paas (2008) supported mental effort measurements and argued that although invested mental effort and perceived task difficulty are related, they may be two distinct constructs, which could lead to potential differences in what is exactly measured. They quoted research findings (e.g., Cennamo, 1993; Paas, Tuovinen, Van Merriënboer, & Darabi, 2005) showing that when a problem is perceived as very difficult, students may lose motivation to make much effort to solve it. However, on the other hand, studies (e.g., Reed, Burton, & Kelly, 1985) also found a low level of invested mental effort as a result of a relatively high level of cognitive load. Therefore, even though it has been argued that mental effort could reflect the actual cognitive load (e.g., Paas, Tuovinen, et al., 2003), the real relationship between mental effort and cognitive load may still remain unclear (Brünken, Plass, & Leutner, 2003).

In spite of such concern about the wording used for the scale, the difficulty scale has been successfully used in many cognitive load theory studies. For instance, Marcus, Cooper, and Sweller (1996) and Ayres (2006) demonstrated that this difficulty rating scale was able to reflect the variations in the levels of element interactivity of tasks, which then may be considered as an indicator for intrinsic cognitive load. Based on the empirical evidence, Sweller et al. (2011) argued that this subjective rating scale, regardless of the different wording, may have shown its high reliability and sensitivity to detect changes in the cognitive load imposed by different instructional materials.

Basically, the subjective rating scale commonly administered in cognitive load theory studies is used for an indication of overall cognitive load. Although the attempts to separately measure each type of cognitive load have been made, the possibility of having reliable and sensitive measures for individual cognitive load may remain debatable (Kirschner, Ayres, & Chandler, 2011). For instance, Amadieu, Mariné, and Laimay (2011) used a combined measurement consisting of a mental effort 9-point scale and five perceived difficulty 9-point scales to investigate the influence of cuing on cognitive load—extraneous cognitive load in particular. They found no significant differences on the mental effort measure, but significant effects were shown on the difficulty scales, which led to their conclusion that a perceived difficulty scale might be more sensitive to changes in extraneous cognitive load. On the other hand, DeLeeuw and Mayer (2008) argued that, given cognitive load is a multidimensional construct, it is possible that a certain measure is more sensitive than others to detect changes in a certain type of cognitive load. They used a mixed approach to separately measuring cognitive load and found that a difficulty rating was most sensitive to changes related to germane cognitive load. In a study by Gerjets, Scheiter, Opfermann, Hesse, and Eysink (2009), a difficulty rating scale was used to assess intrinsic cognitive load. In the three cases above, similar difficulty rating scales were expected to assess different types of cognitive load. Such inconsistency in the measurement suggests that these attempts to separately measure cognitive load still have not yet yielded convincing evidence for a valid and reliable differential measure of cognitive load (Kalyuga, 2011).

Sweller (2010b; Sweller et al., 2011) has argued that separately measuring categories of cognitive load psychometrically is difficult, or even impossible, for it requires students to indicate whether the load they are experiencing is due to which particular category of cognitive load; an instructional designer may be able to make such distinctions, but these will be beyond the ability of students who know little about instructional design principles. Leppink, Paas, Van der Vleuten, Van Gog, and Van Merriënboer (2013) recently developed a ten-item self-report scale; different items are intended to measure different types of cognitive load (see also Leppink, Paas, Van Gog, Van der Vleuten, & Van Merriënboer, 2014). However, the suitability of such a questionnaire for experiments involving children, such as those who participated in the experiments in the present thesis, is unclear. As an alternative, Sweller (2010b) suggested that hypotheses regarding variations in different aspects of cognitive load may be obtained through randomized, controlled experiments. For instance, by altering one category of cognitive load while keeping the others constant, variations in overall cognitive load could be an indication of that particular category of cognitive load (cf. Ayres, 2006) (Kalyuga, 2011; Sweller, 2010b). With the success of the self-reported rating-scale method used in cognitive load theory-based studies, at present it may be most reasonable to indirectly measure variations in sources of cognitive load in this manner when children participate in experiments.

The majority of studies based on cognitive load theory have been conducted with university students or adults; as a result, the validity of the commonly used single item self-rating scale has not been convincingly established when using younger age students as participants. Recently, Van Loon-Hillen, Van Gog, and Brand-Gruwel (2012) developed an illustrated 4-point cognitive load rating scale for the primary school age participants in their experiment. Instead of rating their perceived task difficulty or invested mental effort, the young participants were asked to indicate how ‘‘heavy’’ they found the tasks they just finished, ranging from (1) not at all (with an illustration of a smiling girl carrying one block above her head) to (4) very heavy (with an illustration of a sad-looking girl carrying four blocks above her head). In this experiment, no significant differences were shown in perceived cognitive load between the experimental and the control groups, but a difference in cognitive load between the pretest and the posttest was found. Based on the results, Van Loon-Hillen et al. (2012) concluded that their self-rating scale with graphical expressions seemed to be adequate for measuring cognitive load of younger age participants; however, the sensitivity of the scale might increase if more response options, rather than 4 options, could be provided. Their attempt to measure younger students’ cognitive load with a pictorial rating scale provides a starting point for designing the self-rating scale used in the series of experiments in this thesis.

In the recent revolutionary upgrade, cognitive load theory argues that the mechanisms underlying human cognitive architecture and human knowledge development can be explained by five principles. These principles and their implications for facilitating information acquisition will be discussed next. In addition, cognitive load theory has generated various techniques, termed as the cognitive load effects, to manipulate cognitive load and hence learning. In support of the current research program, three of the effects—the worked example effect, the split-attention effect and the modality effect—which are relevant to the series of studies will be also discussed in the following section.

3.5 Cognitive Architecture Principles

From a biological, evolutionary perspective, human cognition has been driven by natural selection. Human cognitive architecture, as a natural information processing system, has evolved to mimic the information processing structures and procedures used by biological evolution in natural systems. The underlying mechanisms can be specified by the following five basic principles (Sweller, 2003, 2004; Sweller & Sweller, 2006).

3.5.1 The information store principle. Natural information processing systems, like all information processing systems, are in charge of organizing information that governs the activity of entities (e.g., animals, plants) and coordinates their activity with constantly altering environments. Due to the high complexity and variation of an environment, a natural information processing system must have a large information store to handle all kinds of situations.

In the case of biological systems, a species' biological activity in an environment is determined by the information within a genome. A genome, referring to the complement of a species' genes, is central to genetic activity of a species. To ensure that the behaviour of a species can adapt to their complex surroundings and survive, a genome must contain a massive amount of information (Sweller & Sweller, 2006).

The information store principle indicates that in terms of human cognition, long-term memory serves an analogous function as the biological information stored in a genome, providing an ample store of information to govern how people interact with and function in the external world (Sweller, 2006a, 2012). Just as the biological characteristics of a species are determined by the contents of a genome, individuals' cognitive characteristics, such as perception, thinking, and problem solving, are also determined by the schemas stored in long-term memory (Sweller & Sweller, 2006).

The way the human cognitive system and evolution by natural selection uses stored information provides an example of the resemblance between the two information processing systems. Another example of their resemblance is provided by the role of a genome in evolutionary biology and the centrality of long-term memory to learning. Biological evolution mainly relies on genomic change; if there is no change in a species' genome, there is no evolution. Likewise, when nothing is changed in long-term memory despite an experience, nothing has been learned (Sweller, 2004; Sweller & Sweller, 2006).

3.5.2 The borrowing and reorganizing principle. This principle describes two mechanisms. First, almost all of the information held in long-term memory is borrowed. In order to rapidly build a large information store, reproduction is used in biological evolution. Through reproducing, the information a genome carries is passed on to the next generation. This process ensures the important information required for survival will be immediately available for the new generation. The human cognitive system imitates the process used by biological evolution, assembling a massive amount of information in long-term memory by borrowing information from the long-term memory of other people. Sweller and Sweller (2006) suggested that semantic information (i.e., facts, skills, concept-based knowledge) in long-term memory is mostly borrowed, while episodic information is obtained through personal experiences. The transmission of knowledge can be fulfilled by cultural devices (e.g., books, electronic storage), but more importantly, this knowledge can be transmitted through imitation of other people's behavior.

Humans have evolved physiological systems to handle such imitation. The discovery that the mirror neuron system activates when people either observe or perform an action indicates that observing or imitating other people's action may have an effect on human cognition. Moreover, the mirror neurons also fire when people listen to action-related sentences (Tettamanti, Buccino, Saccuman, Gallese, Danna, Scifo, Fazio, Rizzolatti, Cappa, & Perani, 2005) or imagine making a specific action (Grèzes & Decety, 2001). This system is thought to be responsible for obtaining information for long-term memory by observation and imitation.

Another mechanism the borrowing and reorganizing principle describes is that in most situations, the borrowed information needs to be reorganized, either in the first instance or subsequently (Sweller & Sweller, 2006). In the case of asexual reproduction, all the information of a genome is exactly copied and transmitted to the next generation. However, in the case of sexual reproduction, while the information in a genome borrowed from the previous generation, it has been necessarily reorganized. Likewise, in order to be assimilated and combined with previously stored information as schemas within long-term memory, when humans borrow information from other people, the information is simultaneously reorganized (Sweller, 2012). This process of schema construction and modification has been elaborated by schema theory as the process of learning, as discussed above (Sweller & Sweller, 2006).

The worked example effect. According to the borrowing and reorganizing principle, the most efficient technique for people to obtain the needed biologically secondary knowledge is borrowing from other people through imitating what they do, listening to what they say, and reading what they write (Sweller, 2006b). On the basis of this assumption, cognitive load theory advocates that students should be provided with explicit instruction for constructing knowledge, rather than asking them to find information by themselves through discovery or solving problems. It is argued that learning by observing and imitating how experts solve problems is a much more effective and efficient way of acquiring knowledge, especially for novices (Paas, Renkl, et al., 2003; Sweller 1988, 2004; Sweller & Sweller 2006; Van Merriënboer & Sweller, 2005). Studying worked examples is the ultimate instantiation of this argument and its advantages over learning via problem solving have been demonstrated by a substantial amount of empirical studies on many occasions (Kirschner, Sweller, & Clark, 2006; Sweller, 2006a, 2012).

The worked example effect (Cooper & Sweller, 1987; Sweller & Cooper, 1985) occurs when learning is facilitated by studying worked examples. Well-designed examples directly provide students with solutions to problems, which students can then learn. Instead of randomly devising their own solutions and then testing for effectiveness, students borrow problem solutions from experts' long-term memory, a more effective and efficient way to acquire information. These borrowed solutions act like substitute schemas, which are not yet available to inexperienced students, guiding students to construct their own schemas (Kalyuga, Chandler, Tuovinen, & Sweller, 2001). Sweller and Cooper (1985) argued that conventional, goal-directed problem solving would engage students in an enormous amount of means-ends problem solving search and not guide students' attention to the proper aspects of a problem that directly contribute to schema acquisition, causing undesirable extraneous cognitive load. In contrast, the use of worked examples can ensure students' attention is paid to the recognition of problem states and the best associated moves, thus hastening effective schema construction and reducing the possibility of creating extraneous cognitive load (Chandler & Sweller, 1991; Sweller, 1988; Sweller et al., 1998).

The worked example effect has been extensively demonstrated in various domains of studies (e.g., Carroll, 1994; Kyun, Kalyuga, & Sweller, 2013; Miller, Lehman, & Koedinger, 1999; Paas, 1992; Paas & Van Gog, 2006; Paas & Van Merriënboer, 1994b; Pillay, 1994; Quilici & Mayer, 1996; Van Gog, Paas, & Van Merriënboer, 2006). Students who are presented with worked examples to study rather than the equivalent problems to solve perform better in solving subsequent similar problems and/or transfer tests. Cooper and Sweller (1987) suggested that providing students with a large number of worked examples is more effective than providing only a few worked examples followed by a relatively large number of conventional problems, especially for facilitating automation and transfer. Later, Sweller (2006a) further noted that providing only one worked example for one instructional section does not result in the worked example effect. Typically, worked examples are followed by practice problems to test whether students have learned the material. Practice problems can also serve as stimulation for students to actively process worked examples (Sweller & Cooper, 1985; Trafton & Reiser, 1993; Van Gog, Kester, & Paas, 2011).

3.5.3 The randomness as genesis principle. Reorganizing borrowed information, strictly speaking, renders new combinations of old information, instead of creating new information. Therefore, the randomness as genesis principle provides a mechanism for creating new information. This procedure of creativity is necessary for information processing systems because the previously organized knowledge may not be available in some occasions (Sweller & Sweller, 2006).

In the case of evolution by natural selection, an original biological variation is created by random mutation. A new genetic code is randomly generated and has to be tested for adaptability. The new code will be retained if it is adaptable; otherwise, it will be discarded (Sweller, 2006b, 2012). As for human cognitive systems, new information is randomly generated during problem solving, using a similar random generate-and-test procedure used by biological evolution. When people solve a problem, previously stored schemas in long-term memory that are useful for generating possible moves to attain the ultimate goal from the current state will be used. If prior schemas are not available to indicate the legal moves to solve a problem, problem solvers will have to randomly generate moves and then test whether the random moves are useful in reducing the difference between the current and goal states. Useful moves along with those states will be retained, while useless moves will be abandoned. In this manner, new information is thus created and will be incorporated into long-term memory for subsequent use. However, in fact, a pure random generate-and-test strategy is rarely used; in most circumstances, the moves for solving a novel problem are usually a combination of prior knowledge and random generation. If at least some prior knowledge to reduce the huge number of possible moves that need testing is unavailable, many problems are unlikely to be effectively solved (Sweller, 2012).

In effect, the randomness as genesis principle provides the genesis of all novel information that depends on random generation and the following tests for effectiveness. The borrowing and reorganizing principle, on the other hand, makes possible the transfer of generated information. During the transfer process, information from one store may combine with information from other stores, resulting in new combinations of old information. These two principles cooperate to build a large storehouse of information for an information processing system (Sweller & Sweller, 2006).

3.5.4 The narrow limits of change principle. Although the randomness as genesis principle is necessarily used to create new information, the processes of random generation and tests of effectiveness have structural consequences. When prior knowledge is completely unavailable for solving a problem, any random generation will be a potential legal move for effectiveness testing. In a case that three elements can be randomly chosen to generate a move, six possible moves will be produced for testing. If there are a lot of elements for random combinations, it may be unlikely for a time-constrained system to function well, as there will be a huge amount of possible moves for testing. That is why the narrow limits of change principle provides the mechanism to prevent too many elements from being considered simultaneously, as it is impossible to find appropriate combinations while dealing with many elements at a time. As a result of this limitation, only limited changes to an information store will be allowed, and the process of change will be slow (Sweller, 2006b; Sweller & Sweller, 2006).

In biological evolution, successful mutations occur slowly with small genetic changes for effectiveness testing over generations. A rapid and large number of changes to a genome are unlikely to be successful. To monitor the rate of mutations, the epigenetic system exists to control the interactions between the environment and the genetic system, and to determine the time, the location and the way a mutation occurs. Likewise, human cognitive architecture has a highly limited working memory to play the intermediary role between the environment and long-term memory, ensuring the human cognitive system functions effectively. As a result of working memory's limitations in duration and capacity, only a small amount of novel information can be processed in working memory at a time, preventing large, rapid, untested random changes from occurring in the information store. In this sense, changes to long-term memory are slow, small but incremental (Sweller, 2003, 2006b, 2012; Sweller & Sweller, 2006).

The split-attention effect. Considering the limitations of working memory when handling novel information, instructional procedures and materials should be designed to make the best of working memory resources. As mentioned above, using worked examples to directly provide students with the procedures needed to solve problems can avoid the extraneous cognitive load imposed by a problem solving search. However, the effectiveness of worked examples heavily depends on the presentation format. Ill-designed worked examples are less effective than solving equivalent problems; they could impose a heavy extraneous cognitive load. For example, presenting mutually dependent materials in separate source formats could split students' attention. Another instructional principle of cognitive load theory—the split-attention effect—is generated by presenting physically integrated elements of information (e.g., diagrams and associated text), reducing the need for the learner to engage in extraneous "search and match" mental processes (Chandler & Sweller, 1991; Sweller & Chandler, 1994). Cognitive load theory assumes that working memory resources will not be available for real learning if they are consumed by searching for, and integrating, relevant interacting elements to derive meaning from instructional materials. In a meta-analysis of split-attention experiments, Ginns (2006) found that reducing split-attention has a large effect especially on learning with complex instructional materials.

The split-attention effect emphasizes the relations between sources of information within a learning task. It was first demonstrated using geometry materials consisting of diagrams and text (see Sweller, Chandler, Tierney, & Cooper, 1990; Tarmizi & Sweller, 1988). Furthermore, it has been demonstrated by integrating sets of textual materials (e.g., Chandler & Sweller, 1992), combining physics equations with problem statements (e.g., Ward & Sweller,1990), and placing all instruction either on a computer screen or in a hard-copy manual (e.g., Cerpa, Chandler, & Sweller, 1996; Sweller & Chandler, 1994). One consideration that should be noted is that the spit-attention effect applies to the case that a task is unintelligible until all the sources of information integrated together. If a learning task is intelligible without the need of integrating multiple sources of information, there is no advantage to such integration (Sweller, 2012). The redundancy effect, another cognitive load effect generated through a focus on extraneous cognitive load, was proposed to describe such problem when students are provided with additional unnecessary information. Students, especially novices, are normally unaware of the unneeded information so tend to pay attention to and process the information, which does not lead to better learning but interferes with the primary intended learning (for examples, see Chandler & Sweller, 1991; Kalyuga, Chandler, & Sweller, 1999, 2004).

The split-attention effect has been consistently generated using materials presented entirely in a visual format. However, developments in information and communication technologies (ICTs) have supported an alternative redesign for reducing the negative effects of split-attention, based on targeted use of different sensory modes in working memory.

The modality effect. Until the second half of the 1990s, cognitive load theory almost exclusively concentrated on the intention to reduce extraneous cognitive load (Schnotz & Kurschner, 2007). While the majority of early cognitive load theory-inspired instructional redesigns focused on reducing or eliminating extraneous cognitive processing (i.e., processing unrelated to learning) to free up working memory capacity, the modality effect (Mousavi, Low, & Sweller, 1995) takes an alternative approach to ameliorating split-attention by increasing working memory capacity.

According to the working memory model by Baddeley (1986), which cognitive load theory adopts, working memory is a multi-component system incorporating at least two partially independent but limited processing systems—the phonological loop for verbal input and the visuo-spatial sketchpad for visuo-spatial input. Mousavi et al. (1995) suggested that if both information processing channels are employed, some of the cognitive load can be shifted away from one processor to the other. Based on the modality effect, a written explanatory text and an associated visually presented diagram (unimodal—only visual system) could be replaced with a spoken explanatory text referring to the diagram (multimodal—auditory and visual systems) (Sweller, 2012; Van Merriënboer & Sweller, 2010). The results from a meta-analysis of the modality effect have shown that students who learn from instructional materials using graphics with spoken text outperform those who learn from graphics with printed text (Ginns, 2005).

Cognitive load theory holds that the principle underlying the modality effect is the expansion of working memory capacity, resulting from presenting information in multiple modes. There is a potential capacity increase while each modality is used. Penney (1989) reviewed literature on the modality effect and presented the *separate-streams hypothesis* to emphasize that verbal information presented to the auditory and the visual modalities is actively processed in separate streams within short-term memory. Clark and Paivio (1991) argued that partially independent limited processing channels could be optimized to process more information if new information is divided through different sensory modalities. In contrast, if all the information is presented in one single format, the associated processing system might be overloaded and thus learning will be impeded. Mayer's (2001) cognitive theory of multimedia learning supports the modality effect and suggests that providing information in dual-mode presentation may lead to richer referential connections between visual and auditory information, which are temporarily represented within working memory before being integrated with prior knowledge, and hence will facilitate meaningful learning.

The modality effect is particularly important when the material is difficult and unfamiliar, or presented at a pace that is not under students' control. Moreover, larger modality effects are found for higher element interactivity materials than lower element interactivity materials (Ginns, 2005). While learning high element interactivity materials, multiple-mode materials effectively generate additional cognitive resources to tackle the existing interacting elements for schema construction. On the other hand, by expanding the cognitive capacity available for learning, students are more likely to learn complex materials, dealing with highly interacting elements of tasks (Clark & Paivio, 1991; Sweller, 2012).

Based on the premise that each modality has its associated working memory, Baddeley (1990) acknowledged, in addition to the visuo-spatial sketchpad and the phonological loop, which have received the most empirical attention, there may be further subsystems for other types of sensory inputs. However, although the working memory model used by cognitive load theory may incorporate storage and processing modules for input from other modalities, the use of different sensory modes, such as the sense of the body (kinesthetic sense) and of touch (tactile sense), for understanding and learning has not been investigated by cognitive load theory researchers. The present thesis thus expands on previous cognitive load theorizing to explore the instructional design potentials of kinesthetic and tactile working memory channels. Drawing on Baddeley's (2012) recent speculation upon the haptic channel within the visuo-spatial sketchpad, it is assumed in the thesis that the additional information received from the haptic channel would be integrated with the visuo-spatial information within the sketchpad and accordingly constructs better quality schemas. This assumption is founded on, but different from, the classical modality effect. More specifically, they both suggest that presenting information across different sensory modalities may generate more cognitive resources to enhance learning. However, the fundamental difference is the current hypothesizing focuses on the mechanism of incorporating input from multiple sensory modalities to enhance visual processing and hence schema construction. In contrast, hypothesizing regarding the modality effect emphasizes using multiple processing channels to avoid overloading the visual channel specifically, by spreading the processing load across visual and auditory channels.

3.5.5 The environmental organizing and linking principle. The environmental organizing and linking principle provides a link between the environment and the information store. The demands of the environment determine which information needs to be retrieved from the information store; the stored information is then used to determine what action is appropriate to act and function in the environment (Sweller, 2012).

In biological evolution, there is the epigenetic system in charge of organizing the genetic system to coordinate with the environment. The genetic information, which determines the structures and the functions of cells, is arranged and linked to the stimuli from the environment. In doing so, each cell will be guaranteed to properly function for its environment. In human cognition, working memory plays the same intermediate role as the epigenetic system between the environment and the information store. Working memory receives information from the environment to determine which information within long-term memory is accessed to take action appropriate to the environment. In other words, the environmental organizing and linking principle provides the rationale for the existence of human cognitive architecture, for it allows people to use previously stored knowledge to function in the complex outside world (Sweller, 2006b, 2010a, 2012).

There is a difference in the ways working memory handles environmental information and stored information in long-term memory. While dealing with novel information from the outside world, working memory has severe limitations in capacity and duration. However, the working memory constraints disappear when dealing with familiar, organized information from long-term memory. Prior knowledge stored in long-term memory serves as a central executive to indicate what information needs to be used and how it is processed to decide action; thus, the need for random generation is eliminated. Since random generation and the associated testing for effectiveness are not required while handling familiar organized information in long-term memory, working memory limits, as the narrow limits of change principle suggests, disappear. That is to say, the characteristics of working memory are changed by the sources of knowledge from highly-limited to perhaps unlimited (Sweller, 2012; Sweller & Sweller, 2006).

To account for the change in working memory's characteristics, Ericsson and Kintsch (1995) proposed a separate memory structure—long-term working memory—to allow a large amount of information from long-term memory to be rapidly processed. The expanded capacity of working memory is restricted to skilled performance and is tailored to the specific demands for skilled activities. While approaching a given skilled task, experts are capable of immediately retrieving associated schemas and bringing a large amount of information into a corresponding just-formed long-term working memory. This means that experts in a given domain not only possess ample domain-specific knowledge but also acquire particular encoding skills for organizing information in an effective manner so that the information can be accessed rapidly with retrieval cues. In this sense, working memory capacity is not fixed; it is determined by levels of expertise in a domain.

In summary, the borrowing and reorganizing principle and the randomness as genesis principle explain how working memory acquires information from the environment and stores that information into long-term memory; the environment organizing and linking principle explains how working memory accesses information from long-term memory to generate appropriate action required by the environment. From an evolution-oriented perspective, cognitive load theory holds that these five biological evolutionary principles can apply for the procedure used by biological evolution and by human cognitive architecture to deal with information. They provide strong support for the validity of the postulated human cognitive architecture. More importantly, from an instructional design perspective, the five principles provide an evolutionary foundation for explaining existing cognitive load effects, as well as generating and testing novel hypotheses (e.g., Youssef, Ayres, & Sweller, 2012).

3.6 Using Biologically Primary Knowledge to Acquire Biologically Secondary Knowledge

As previously discussed, the limitations in capacity and duration of working memory only apply to the acquisition of biological secondary knowledge. In contrast, acquiring biologically primary knowledge is less affected by the working memory restrictions (Sweller, 2008). Humans can easily acquire a large amount of biologically primary knowledge without instruction or extrinsic motivation. Considering the efficiency of the primary systems for acquiring biologically primary knowledge, it is argued that using primary knowledge to facilitate the acquisition of secondary knowledge may be advantageous for making use of the primary systems and so reducing the impacts of the working memory limitations (Geary, 2008; Paas & Sweller, 2012).

3.6.1 Communication. The first example of using biologically primary knowledge to facilitate the acquisition of biologically secondary knowledge relates to human communication. According to the borrowing and reorganizing principle, most of the information within an information store is borrowed (Sweller, 2004; Sweller & Sweller, 2006). In this manner, humans build up their long-term memory by borrowing information from other people’s long-term memory. In the context of individual learning, cognitive load theory has demonstrated the borrowing and reorganizing principle by providing students with worked examples and so allowing students to borrow problem solutions from experts (Cooper & Sweller, 1987; Sweller, 1988; Sweller & Cooper, 1985). Recently, from an evolutionary perspective, cognitive load theory researchers proposed the collective working memory effect, suggesting that students can obtain information more effectively by studying collaboratively, when dealing with a task imposing a high cognitive load. While the capacity of a single working memory is limited, multiple working memories working together could have more cognitive resources to carry out a learning task. In other words, as the cognitive load imposed by a learning task is distributed among a group of people, the cognitive effort that each group member has to invest is reduced. Therefore, collaborative learning is considered as a way to overcome individual working memory limitations (Janssen, Kirschner, Erkens, Kirschner, & Paas, 2010; Kirschner, Paas, & Kirschner, 2009a, 2009b, 2011; Kirschner, Paas, Kirschner, & Janssen, 2011). For obtaining information from other people, humans have evolved to possess the ability of communication as biologically primary knowledge. In a collaborative learning environment, the communicating ability is imperative for group members to divide and coordinate information.

Since communication is a biologically primary skill, it requires relatively low cognitive effort. Thus, when a task for acquiring biologically secondary knowledge is high in complexity, it would be more efficient to learn such task collaboratively by distributing the needed mental effort but with a little cognitive cost for communication (Kirschner, Paas, & Kirschner, 2011). It should be noted that if a task only imposes a low cognitive load, meaning that individual learners have sufficient cognitive resources to handle all the information by themselves, adding an extra cognitive load by having interpersonal communication is unnecessary. In this case, individual learning is more efficient than collaborative learning (Paas & Sweller, 2012; Sweller et al., 2011).

3.6.2 Observation and imitation of human movement. The second example of biologically primary knowledge for assisting in acquiring biologically secondary knowledge is the ability to observe and imitate other people's movements. As previously mentioned while discussing the borrowing and reorganizing principle, in order to borrow information, humans have evolved a mirror neuron system to handle observation and imitation of others' behavior. It is found that the same mirror neurons will respond while executing or observing a certain action (for a review, see Rizzolatti & Craighero, 2004). Cognitive load theory has termed this neuroscience finding as the human movement effect (Paas & Sweller, 2012). With the assistance of this evolved primary skill, humans are ready to acquire secondary knowledge involving human movements more efficiently by imitation, compared with the knowledge involving non-human movements.

Initially, the human movement effect was reported as a special case, which is inconsistent with the argument that cognitive load theory has made about the ineffectiveness of instructional animations caused by transient information presentations. Cognitive load theory generates the transient information effect to reflect the finding that learning is hindered because transient information does not allow students enough time to process it adequately and causes a high extraneous cognitive load (Ayres & Paas, 2007). When the information is transient and important for learning, students will have to try to remember the information and then link it with new information to obtain understanding. If the information is extensive and high in element interactivity, many elements of information will need to be held and integrated in working memory. In this circumstance, working memory will be easily overloaded (Leahy & Sweller, 2011; Sweller et al., 2011). The excessive cognitive load caused by transient information often occurs in instructional animations. However, counter to the transient information effect, the meta-analysis of Höffler and Leutner (2007) showed a medium-sized overall advantage of dynamic representations in instructional animations over static representations, when the animations were highly realistic and/or involved procedural-motor knowledge. Accordingly, the human movement effect is suggested to be a cognitive load approach to overcoming the transient information effect. To be specific, despite the negative impacts of transient information on learning, when secondary learning tasks involve human motor skills, dynamic representations will be superior to static representations, because the human brain has been primed by the mirror neuron system to learn from observation and imitation (see Ayres, Marcus, Chan, & Qian, 2009; Van Gog, Paas, Marcus, Ayres, & Sweller, 2009; Wong, Marcus, Ayres, Smith, Cooper, Paas, & Sweller, 2009).

3.6.3 Hand movement. The third example of biologically primary knowledge used to facilitate the acquisition of biologically secondary knowledge can be explained by the notion of embodied cognition. As discussed in Chapter Two, embodied cognition perspectives hold that human cognition is grounded in sensorimotor experiences gained from interactions between the body and the environment through human perceptual and motor systems (Barsalou, 1999; Glenberg, 2010; Wilson, 2002). Moreover, although body-environment interactions could take on various forms, humans primarily and mostly use the hands to gather sensorimotor experiences (e.g., in the forms of gesturing and object manipulation). The ability to physically interact with the environment can be categorized as biologically primary knowledge, since this ability is one that naturally develops without explicit instruction for the vast majority of healthy individuals. To date, a substantial number of studies have demonstrated the positive impacts of making hand movements on the performance of cognitive tasks, such as reading comprehension (e.g., Marley et al., 2010), mathematics (e.g., Goldin-Meadow et al., 2001), counting (e.g., Alibali & DiRusso, 1999) and problem solving (e.g., Beilock & Goldin-Meadow, 2010). Each of these findings can be considered as an illustration of biologically primary knowledge assisting in acquiring biologically secondary knowledge.

It is important to clarify that the cognitive benefits of hand movements are not limited to spontaneous gestures; studies have shown that using instructed hand movements also brings benefits to learning tasks (e.g., Broaders et al., 2007; Cook et al., 2008; Hulme, 1981a; McGregor et al., 2009). Perhaps, since performing hand movements is a well-developed primary skill, it is relatively easy and requires minimal mental effort to acquire a new hand movement. It is true that biologically primary knowledge is assumed to be unteachable, for instance, a general problem solving skill—means-ends analysis. However, in some cases, even though humans have not yet evolved to automatically acquire a specific skill, they are capable to learn the skill immediately and use it to other similar situations, after watching someone else demonstrate it once, such as opening a milk carton. Such type of skill, though learned by being taught, could be taken as biologically primary (Paas & Sweller, 2012). The same rule should be applied to the case of an instructed hand movement.

In addition, the acquisition of biologically secondary knowledge not only can be facilitated by using the primary skill of making hand movements, but also by seeing other people using this skill; co-speech gestures is a case in point. With the use of gestures, interpersonal communication in an educational context improves and so learning is enhanced (Hostetter, 2011). It has been argued that, due to the existence of the mirror neuron system, listeners are capable to understand the meanings and the intentions of the gestures that speakers produce (Rizzolatti, 2005; Rizzolatti & Craighero, 2004). Even children at a very young age are capable to understand an action intention made by others. For instance, as mentioned earlier, 12-month-old infants already could comprehend the intention of a pointing gesture (Liszkowski & Tomasello, 2011).

Indeed, a pointing gesture is probably the first intentional gesture that people start to use and understand since infancy. Across the life-span, people frequently use pointing in contexts such as conversation or reading to make references or guide attention. Recently, Macken and Ginns (in press) found that adult participants studying expository text and diagrams on heart anatomy in physiology achieved higher scores on subsequent terminology and comprehension tests when they used their finger to point to related elements of the text and diagrams, as well as trace out the blood flows marked by arrows in the diagrams. Similarly, recent research in computer-based instruction has shown that using a human pointing movement as an attentional cue results in better learning. For example, Moreno, Reisslein, and Ozogul (2010) found that students who studied the computer-displayed instruction in which relevant parts were guided by a deictic movement of an animated avatar’s arm had the best performance in the posttest and reported the lowest perceived difficulty during learning. In contrast, when instruction was guided by an animated arrow or without any visual guidance, students’ performance was worse and their perceived learning difficulty was higher. Similar results were also obtained by de Koning and Tabbers (2013) using dynamic animation-based instruction. Their study showed that observing a human hand following the movements in a lightning animation yielded better retention and transfer performance, compared with observing a pointing arrow. de Koning and Tabbers (2013) suggested that seeing a real human hand movement is more likely to activate the cortical circuits involved in moving the viewers' hand, which helps to ground the movements in the animation into the viewers' motor system. Consequently, the quality of their mental representations of the instructional animation improves, leading to better learning outcomes. Johnson, Ozogul, Moreno, and Reisslein (2013) found that using a human pointing movement as a visual cue in instructional materials could substantially improve the learning of students with lower prior knowledge, though students with higher prior knowledge did not particularly benefit from this instructional technique, suggesting a potential expertise reversal effect (Kalyuga, 2007; Kalyuga & Renkl, 2010).

In summary, findings of the positive effects on attention and learning of a human pointing movement apparently constitute a good example of biologically primary knowledge supporting the development of biologically secondary knowledge, and are also consistent with contemporary embodied cognition perspectives that human body movements affect cognition and learning.

3.7 Summary

This chapter provides an overall review of cognitive load theory. The first part discussed the evolutionary view of biologically primary knowledge and biologically secondary knowledge. The second part discussed the structure of the human cognitive system. The third part discussed distinctions between intrinsic, extraneous, and germane cognitive load, as well as the ways cognitive load may be measured. The fourth part reviewed the five principles underlying human cognitive architecture and biological evolution. Three cognitive effects relevant to the series of studies were also reviewed. The final part discussed the cases in that biologically primary knowledge is used to facilitate the acquisition of biologically secondary knowledge.

The central tenet of cognitive load theory is that the design of instructional materials should align with human cognitive architecture. Over the past three decades, cognitive load theorists have generated a range of cognitive load effects to improve instructional design, making optimal use of limited working memory. Recently, cognitive load theory has incorporated evolutionary theory and upgraded its theoretical framework based on biological evolution. Currently, the most important educational implication—which lays a foundation for the experiments in this thesis— is the contention that the acquisition of biologically secondary knowledge can be facilitated with the assistance of biologically primary knowledge. According to this idea, moving the hands to express information and feelings, to explore the environment, and to manipulate objects is a primary skill, which can be used to assist in acquiring biologically secondary knowledge. This idea is clearly consistent with the central stance of embodied cognition that human cognition is grounded in physical interactions between the body and the environment. Based on the theoretical frameworks of cognitive load theory and embodied cognition, the main hypothesis of the present research project is that incorporating tracing movements into worked example-based learning to acquire secondary knowledge in the domain of mathematics will result in the construction of more effective schemas, indicated by enhanced test performance and reduced test difficulty.

The hypothesized tracing effect is strongly supported by the literature reviewed in Chapter 2 and 3. Given the natural phenomenon that humans typically start to use pointing in infancy without deliberate instruction to support daily cognitive activities, it is reasonable to posit that holding a pointing finger to trace the surface of instructional materials belongs to the category of biologically primary knowledge. Instructing students to use their pointing finger to trace worked examples requires no specific training and this added procedure should place little or no demand on conscious cognitive resources, but through exploiting biologically primary systems, the tracing instructions could facilitate the acquisition of secondary knowledge in several ways. First, using the finger to trace worked examples may be a powerful and effective means of directing attention across different modalities to the location of relevant information for further processing, which could reduce visual search and avoid waste of cognitive resources. Second, by putting the hands near the instructional materials, the bimodal visuotactile neurons that humans possess could influence visual attention to alter the processing of information such as faster recognition and prolonged scrutiny, which may then lead to deeper learning. The fact that humans own such a biologically founded processing mechanism apparently provides further support for the argument that using the hands while engaging in cognitive activities is a biologically primary skill that humans have evolved to naturally acquire with supportive physical systems. Third, tracing worked examples would bring in information from the haptic modality to join visuo-spatial information within the visuo-spatial sketchpad and accordingly upgrade schema construction. Lastly, the schema construction at the acquisition phase would be enhanced by using tracing to reduce element interactivity through chunking disparate elements of instructional information into a single schema, which later will be more easily retrieved into working memory and held active to solve problems, generating lower levels of intrinsic cognitive load at the test phase.

The central hypothesis of this thesis is examined by a series of experiments, presented across the next four chapters. Experiment 1 investigated whether the incorporation of tracing into learning from worked examples on angle relationships involving parallel lines would enhance learning, compared with simply studying worked examples without tracing. Students in the tracing condition were expected to outperform those in the non-tracing condition at the posttest and also report a lower level of test difficulty. Experiment 2 replicated and refined the first experiment, examining whether tracing could improve worked example-based learning. Younger participants were recruited to better align participants' knowledge level and the experimental materials. The materials instructing angle relationships associated with parallel lines were used again, but the difficulty of the posttest was increased. With the changes to the age group and the test, it was expected that the superiority of tracing while studying worked examples over simply studying worked examples would be shown in test results and test difficulty ratings. Experiment 3 examined the generalizability of the tracing effect obtained from Experiments 1 and 2, using materials instructing angle relationships of a triangle and recruiting slightly older participants. If the results from the previous experiments were generalizable, positive impacts on learning of tracing worked examples would be obtained again. Experiment 4 examined whether tracing with and without the sense of touch would result in different learning outcomes. Instructional materials identical to Experiment 2 were used. It was expected that students in the tracing with touch condition, who learned with visual, tactile, and kinesthetic inputs, would outperform those in the tracing without touch condition, who learned with visual and kinesthetic inputs. The former group would also report a lower level of test difficulty than the latter. Students in the non-tracing condition, who learned with visual input only, were expected to have the lowest level of test performance and report the highest level of test difficulty among the three conditions.

Chapter Four: Experiment 1

The present series of experiments aimed to investigate the impacts on learning of incorporating tracing movements into example-based instruction. Experiment 1 was designed to explore whether a significant difference between instruction with tracing and without tracing could be obtained, using mathematics worked examples instructing angle relationships involving parallel lines.

Based on the worked example effect (Cooper & Sweller, 1987; Sweller & Cooper, 1985), providing worked examples is a more effective and efficient way to teach students how to apply a combination of angle relationships involving parallel lines to calculate a missing angle, especially when students are novices in this topic. Therefore, worked example-based instructional materials were used in Experiment 1 to examine the effects of tracing movements. In addition to simply reading over and comprehending instructional materials, students in the experimental condition were required to study and trace the worked examples with their dominant hand's index finger. Research on the modality effect (e.g., Mousavi et al., 1995; Tindall-Ford, Chandler, & Sweller, 1997) has suggested that presenting information through multiple processing channels may optimize the use of the effective capacity of working memory. By using multiple modalities (i.e., visual and haptic modalities) to undertake the learning task in Experiment 1, improved learning and test performance should result. In addition to generating extra cognitive resources available for use, the presence of a pointing finger could serve as an attentional guide, effectively directing cognitive resources to alter the processing of the most important information near the hands for meaningful learning (Cosman & Vecera, 2010; Reed et al., 2006).

Taken together, it was hypothesized that students in the experimental condition would benefit from the tracing instructions during the acquisition phase through using visual and haptic modalities for learning, rather than the visual modality only, and would consequently have better performance at the test phase. It was also predicted that these students would rate the test questions as less difficult than students in the control condition, reflecting the creation of higher quality schemas during the acquisition phase and lower levels of experienced intrinsic cognitive load at the test phase.

Method

This experiment, and the other experiments presented in this thesis, was approved by the Human Research Ethics Committee of the University of Sydney under Protocol #14236.

Participants. Participants consisted of 56 Year 6 students, including 38 boys and 18 girls, from 2 independent schools in Sydney, Australia. All participants participated voluntarily, and were aged between 11 and 12 years old (M = 11.20, SD = .44).

Participants were novices with respect to the information presented in the instructional materials; they could identify parallel lines and angles but had not learned the angle relationships involving parallel lines at school. All the participants were randomly assigned to the tracing or the non-tracing condition.

Materials and procedure. Students were tested individually, with each student being withdrawn from class for approximately 30 minutes. The experiment began with an initial instruction phase, identical for both groups. This phase was followed by an acquisition phase involving study, with or without tracing, of two worked examples; each worked example was paired by a similar practice problem. The experiment concluded with a test phase of six questions. Each test question was followed by a test difficulty rating. An example of the worked examples is provided in Figure 4.1. The complete materials for both conditions are given in Appendix 1.

***Initial instruction phase*.** The materials used in this phase consisted of four pages of initial instruction about three angle relationships involving parallel lines. Students had 5 minutes to study the three angle relationships, including:

1. Vertical angles are equal.

2. Corresponding angles are equal.

3. The sum of co-interior angles is 180°.

For each angle relationship, instruction was provided, which included a short text providing its definition, diagrams displaying the locations of the specific angles, and an example demonstrating how to use this angle relationship to solve a problem.

Question: What is the value of B?

"Given" angles are in normal type; steps of the solution are in ***italic and bold*** type.

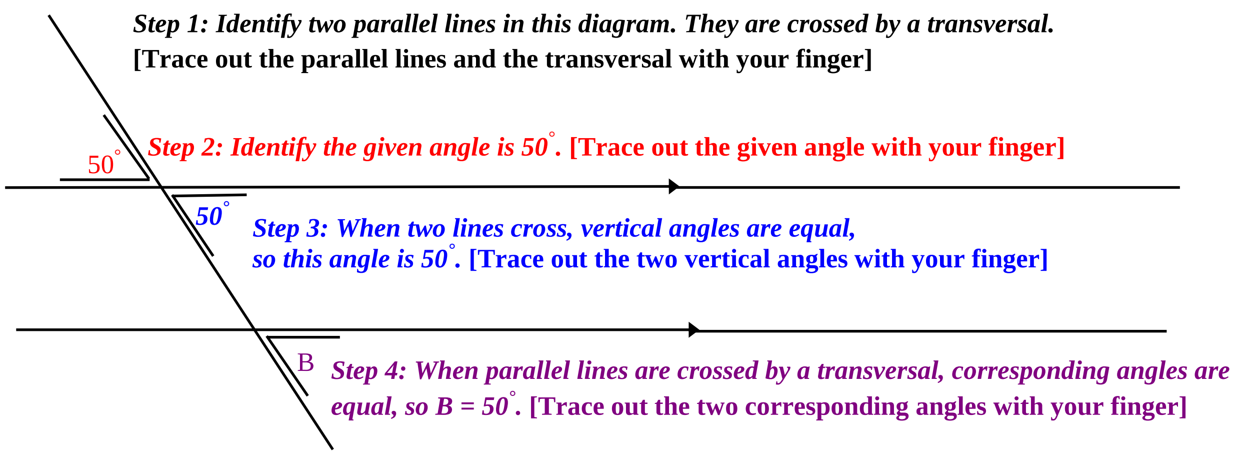

Figure 4.1. One of the worked examples used in Experiment 1 for the tracing condition.

***Acquisition phase*.** All students were then shown two worked examples applying the three angle relationships to find a missing angle. In the worked examples for the tracing group, every solution step was followed by instructions in brackets on tracing. Students in the tracing condition were given 2 minutes to read and try to understand the solution steps, while using their index finger of their writing hand to trace out the diagram following the instructions. For example, after reading "When two lines cross, vertical angles are equal, so this angle is 50°. [Trace out the two vertical angles with your finger]", students had to locate the designated vertical angles and trace them with their finger. Students in the non-tracing condition were instructed to read and try to understand the solution steps for 2 minutes, with their hands placed on their laps.

Each worked example was paired with a similar practice problem, with a maximum of 2 minutes given to solve the problem. Students who provided an incorrect answer were asked to try again within the 2-minute time limit. Students who could not work out the correct answer when the time was expended were stopped. They were required to study the worked example again and then went back to solve the practice problem until the correct answer was attained.

Across the initial instruction and acquisition phases, the materials were designed in accordance with the principles of instructional design previously generated by cognitive load theory to reduce extraneous cognitive load. As the theory argues, many instructional materials require students to split their attention between separate diagrams and text. If the split-source information cannot be comprehended until integrated, students will have to keep the text information in working memory while seeking for the related information in the diagram. This process could cause an unnecessary working memory load. In order to minimize the need for students to engage in extraneous search and match mental processes, the diagrams and the relevant solution steps in the worked examples used in the experiment were physically integrated (see Chandler & Sweller, 1991, 1996; Kalyuga, Chandler, & Sweller, 1998). Another technique that has been used to prevent split attention while studying instructional materials is color coding. Kalyuga et al. (1999) demonstrated that using the same color for the associated information in the text and the diagram could effectively reduce the mental burden caused by split attention. In their study, students who studied the color-coded materials had better test performance and lower rating of learning difficulty than those who studied the conventional materials. Ozcelik, Karakus, Kursun, and Cagiltay (2009) suggested that color coding could make finding corresponding information in the text and in the diagrams easier and also help guide attention to important information for meaningful learning. In the worked examples used in Experiment 1, each solution step and its associated elements in the diagram were colored in the same color. Different colors were used for each text-diagram pair. Color coding was also applied in the initial instructional materials to locate related information between the text and the diagram and to make important information stand out from its surroundings. For example, when being mentioned for the first time, the mathematical term “transversal” in the text and the transversal line in the diagram were both colored in red. In addition to physical integration and color coding, arrows were also used in the experimental materials to connect the text and the diagrams and ensure that students correctly matched the important mathematical terms with the corresponding parts of the diagrams (see Kalyuga et al., 1999).

To reduce the difficulty of calculation, the numbers used in the materials were multiples of 5 or 10. This design decision was made because the focus of the experiment was on alternative designs to assist students in constructing problem solving schemas, not on building mental arithmetic fluency; hence, multiples of 5 and 10 were used to minimize a potential but extraneous source of error.

***Test phase*.** The test phase consisted of two basic questions, with similar diagrams and solution steps to the worked examples but with different numbers, and four advanced questions, which differed from the worked examples with moderate variations in diagrams and the sequence of solution steps. Students had up to 2 minutes to find a solution for each question.

Test item difficulty self-reports. Given that it is advisable to take both cognitive load measures and task performance into account in determining the effectiveness and efficiency of instructional methods (Paas, Tuovinen, et al., 2003; Paas et al., 1994), after each test question, students were immediately asked to rate the difficulty of the question they had just attempted, as an indication of students' intrinsic cognitive load at the test phase; that is, students' experience of working memory load in recalling one or more schemas from long-term memory and keeping it active while solving test problems. Across the experiments in this thesis, a 5-point illustrated subjective rating scale of test difficulty ranging from 1 being "very easy" to 5 being "very difficult" was used. The design of this scale was informed in several ways by the previous attempt made by Van Loon-Hillen et al. (2012) to measure young participants' perceived cognitive load using a 4-point illustrated self-rating scale.

First, considering that it might be difficult for young students to comprehend the concept of "mental effort" in the commonly used 1-item rating scale or the metaphor of "heaviness" used by Van Loon-Hillen et al. (2012), the notion of test question difficulty was used in the current rating scale.

Second, evidence suggests that rating scales paired with images as anchors can facilitate meaningful responses in young children (e.g., Cassidy, 1988; Harter & Pike, 1984; Verschueren, Marcoen, & Schoefs, 1996). Support also comes from the study by Van Loon-Hillen et al. (2012); the illustrated rating-scale used in their study was valid in reflecting the difference in young participants' cognitive load between the pretest and the posttest. Therefore, for the age group of participants in the current experiment, two faces were positioned above the 1 and 5 anchors to help students to indicate how they felt while solving a test question. A smiling face was put on top of the number 1, indicating that a problem has been straightforwardly solved with little conscious effort (i.e., on the basis of suitable schema easily retrieved from long-term memory, generating little intrinsic cognitive load when comprehended in combination with other present elements of the test question). In contrast, a frowning face was put on top of the number 5, intending to capture an expression of considerable concentration during problem solving based on the schema being incomplete and/or difficult to retrieve into working memory, as well as hold active in combination with other present elements of the test question. These two faces were drawn from the Faces Pain Scale—Revised (Hicks, Von Baeyer, Spafford, Van Korlaar, & Goodenough, 2001).

Third, Van Loon-Hillen et al. (2012) suggested that a scale with more answer options would be more sensitive to detect changes, as in their study they failed to find significant differences in cognitive load between the experimental and the control groups with their 4-point rating scale. However, while the number of the points on a scale increases, differences between scale point descriptions will become smaller and accordingly become more difficult to interpret. Therefore, considering the scale sensitivity and the potential difficulty for young participants to interpret the differences between point descriptions, a scale with 5 answer options was developed for this experiment.

In addition, variations in the timing and frequency of rating scale administration have been raised as a concern in cognitive load theory research (Ayres & Paas, 2012). For instance, Van Gog, Kirschner, Kester, and Paas (2012) investigated how the timing and frequency affected cognitive load measures and suggested that repeatedly measuring mental effort after each task can provide more accurate data than measuring only once at the end of a series of tasks. Accordingly, after each test question, participants in this experiment were asked to rate how difficult they had found the question they just attempted. The average of these ratings served as an indicator of the intrinsic cognitive load associated with the test phase.

Data Analysis

Initial checks on the distributional properties of data under analysis consisted of inspection of skewness and kurtosis values, and their associated standard errors. Where the skewness or kurtosis value divided by its standard error was greater than 1.96, a potential violation of the independent groups *t*-test's assumption of normality would be evident (Field, 2005). The Shapiro-Wilks test of normality was also used to evaluate distributional assumptions. Where non-normally distributed results (e.g., for error rates) necessitated the use of a non-parametric test (the Mann-Whitney *U* using an exact *p* value; Mehta & Patel, 2012), a *z*-score associated with the Mann-Whitney test was converted into the effect size *r* and then converted to *d* using the typical transformation for Pearson's *r* to *d* (see Chapter 7 of Borenstein, Hedges, Higgins, & Rothstein, 2009). Where normality assumptions were not violated, the independent groups *t*-test assumption of equality of variances was assessed using Levene's test. If the results of this test were non-significant, analysis proceeded using a standard independent groups *t*-test; if Levene's test was significant, a version of the *t*-test suitable for heterogenous variances provided by SPSS is presented. Analyses of experimental data reported across the present thesis combined tests of significance, controlling the Type 1 error rate at 0.05, with estimates of the standardized mean difference effect size (d). Based on a major review of over 800 meta-analyses of educational research, Hattie (2009) suggested the following benchmarks for effect size magnitude: small $d = 0.20$, medium $d = 0.40$, and large $d = 0.60$ and above.

Results

The variables under analysis were number of correct answers, number of errors, total time for solution to practice problems at the acquisition phase, and number of correct answers, number of errors, total time for solution to test questions, and ratings of test item difficulty at the test phase. Means and standard deviations are provided in Table 4.1.

Table 4.1

Means and (Standard Deviations in Parentheses) for Acquisition Phase Number of Correct Answers, Number of Errors, Time for Solution (Seconds), and Test Phase Number of Correct Answers, Number of Errors, Time for Solution (Seconds) and Ratings of Test Difficulty

Variate	Non-tracing	Tracing
Acquisition Phase		
Number of correct answers	1.71 (.53)	1.96 (.19)
Number of errors	.50 (1.04)	.21 (.42)
Time for solution	122.46 (62.05)	122.21 (57.90)
Test Phase		
Number of correct answers	5.43 (1.17)	5.68 (0.86)
Number of errors	1.46 (1.90)	0.69 (1.25)
Time for solution	322.75 (142.04)	304.43 (140.74)
Test difficulty	2.48 (0.80)	2.26 (0.66)

Acquisition phase. Due to substantial skewness of the data, a Mann-Whitney test was used to analyze number of errors. The mean rank of the tracing condition (Mean rank = 27.57) was not statistically different to that of the non-tracing condition (Mean rank = 29.43), $U = 366.00$, $p = .551$, $d = -.16$. The difference between the tracing condition's total time for solution ($M = 122.21$, $SD = 57.90$) and that of the non-tracing condition ($M = 122.46$, $SD = 62.05$) was also not statistically reliable, $t(54) = -.02$, $p = .988$, $d = -.005$. Given the skewness of the data, a Mann-Whitney test was used to analyze number of practice problems solved; the tracing condition (Mean rank = 31.52) correctly solved more practice problems than the non-tracing condition (Mean rank = 25.48), $U = 307.50$, $p = .045$, $d = .63$.

Test phase. Due to substantial skewness of the data, a Mann-Whitney test was used on the number of errors, favoring the tracing condition (Mean rank = 24.64) over the non-tracing condition (Mean rank = 32.36), $U = 284$, $p = .047$, $d = -.54$. For total time for solution of test questions, a Mann-Whitney test indicated that the difference between the tracing condition (Mean rank = 26.79) and the non-tracing condition (Mean rank = 30.21) was not statistically reliable, $U = 344$, $p = .437$, $d = -.22$. A ceiling effect was shown on test questions correctly answered (78.6 % students correctly solved all questions), preventing analysis of this variable. Lastly, the difference in overall ratings of test difficulty between the tracing condition ($M = 2.26$, $SD = .66$) and the non-tracing condition ($M = 2.48$, $SD = .80$) was not statistically reliable, $t(54) = -1.15$, $p = .255$, $d = -.31$. However, post-hoc analyses of difficulty ratings of individual test questions, using a Bonferroni correction of the Type 1 error rate, found the last question, one of the advanced questions, was rated as less difficult by the tracing condition ($M = 2.04$, $SD = .92$), compared with the non-tracing condition ($M = 2.89$, $SD = 1.26$), $t(54) = 2.91$, $p = .005$, $d = -.78$. The final question consisted of three parallel lines and one transversal, which required applying all the three angle relationships to work out the correct answer, and so would be expected to be quite challenging for novices; hence, most likely to evince a difference in perceived difficulty between the two experimental conditions.

Discussion

Experiment 1 was designed to test if tracing out the graphical elements of geometry worked examples could enhance learning. Students were required to study worked examples applying the angle relationships of parallel lines to solve problems. Instead of studying in a conventional way, simply reading over and comprehending the materials, students in the experimental condition were instructed to use their index finger to trace out the corresponding elements of the diagrams after reading each solution step in the worked examples. It was hypothesized that students who traced elements of worked examples while studying during the acquisition phase would perform better on the subsequent test as measured by the number of correct answers, error rate, and time for solution across the acquisition and test phases. Moreover, it was predicted students in the tracing condition would consider the test items less difficult than students who simply studied the materials without any hand movement, as tracing was hypothesized to promote schema construction and automation. Results partially supported the hypotheses, with students in the tracing condition solving more acquisition phase practice problems and making fewer errors across the six posttest questions than those in the non-tracing condition. In addition, students in the tracing condition rated one of the advanced test items as less difficult than students in the non-tracing condition. This is consistent with the hypothesis that tracing worked examples assists in the construction of problem solving schemas capable of being deployed at the test phase to a greater extent than simply studying worked examples. Although significant differences were not found in total solution time and test difficulty ratings, the data showed a trend in the expected direction—the tracing group used less time for the test and considered the test items less difficult than the non-tracing group did.

The results reported above speak to the importance in instructional design experiments of suitable alignment between the prior knowledge levels of participants and the complexity of the materials and test questions (see Cooper & Sweller, 1987, p. 351). Specifically, the presence of the ceiling effect on overall test performance informs a further alignment between the knowledge level of participants and the difficulty of materials. According to the New South Wales *Mathematics K-10 Syllabus* for the Australian curriculum (Board of Studies NSW, 2012), identifying and naming angles formed by transversals on sets of parallel lines and making use of the relationships between them are the set outcomes for Stage 4 (i.e., Year 7 and Year 8) students. Therefore, presumably, students in Year 6 (i.e., Stage 3) had not yet been introduced to the angle relationships of parallel lines in school. One possible explanation for the high test scores in Experiment 1 is that students at the late Stage 3 might have built up sufficient prior knowledge to learn this topic, so they could grasp the new information swiftly, though this topic is scheduled for Stage 4 students. Another possible reason for misjudging students' knowledge level is that students who attended tutoring schools might have been exposed to the information related to the properties of parallel lines in advance. Even though they might not have learned all the angle relationships presented in the instructional materials in Experiment 1, they might already have some relevant knowledge, which supported them in completing test questions with relative ease.

The high level of test performance informs two approaches for improving the design of the next experiment. First, since students at late Stage 3 may have sufficient prior experience for them to learn the properties of parallel lines without too much difficulty, recruiting early Stage 3 students with less experience may circumvent the ceiling effect on test scores. The second approach is to increase the difficulty level of the test with more advanced questions so that students will have to apply the angle relationships to work out correct answers more flexibly. This may have the effect of reducing the accuracy rate and increasing the error rate.

In summary, it was expected that replicating the present experiment with younger students and a more challenging test would yield significant differences between the experimental and control conditions. This hypothesis was tested in the next experiment.

Chapter Five: Experiment 2

Experiment 1 explored the effectiveness of incorporating tracing into instruction, finding that explicitly instructing students to trace out elements of worked examples enhanced learning as indicated by better performance on practice problems during the acquisition phase, as well as a lower error rate during the posttest. The results provided tentative evidence for the beneficial role of tracing while learning from worked examples, suggesting that studying worked examples with tracing was more effective than without tracing on some, but not all, variates.

Experiment 2 aimed to generate a stronger tracing effect. Informed by the results of Experiment 1, the first priority of Experiment 2 was to seek a better match of experimental materials and participants to test the research hypotheses. According to the New South Wales mathematics syllabus, applying the properties of parallel lines to solve problems are scheduled for Stage 4 students (i.e., Years 7-8). However, Year 6 students could already have the preliminary knowledge of associated angle relationships involving parallel lines, so the instructional materials in Experiment 1 may not have been challenging enough for Year 6 students, especially for students with greater mathematics ability. Thus, Year 5 students, who could reasonably be expected to have less knowledge of angles and parallel lines, were recruited for the present experiment.

The experimental materials used in Experiment 1 were used again, but with some modifications to make the initial instructions more readily understandable for younger students. In addition, to deal with the ceiling effect in Experiment 1, the difficulty of the test was increased, with more challenging questions and a shorter time limit for answering each question. It was expected that, with a more difficult test and less experienced participants, significant differences in test performance between the tracing and the non-tracing groups would be obtained.

Method

Participants. 42 Year 5 students aged between 10 and 11 years old (*M* = 10.50, *SD* = .51) from an independent boys' school in Sydney, Australia, voluntarily participated in this experiment. Participants were novices with respect to the angle relationships in the instructional materials. They were randomly assigned to the tracing or the non-tracing condition.

Materials and procedure. Similar instructional materials to those used in Experiment 1 were used, but a few changes were made. First, considering the literacy ability of young students, difficult words and long sentences were replaced with simpler words and sentences. For example,

Instruction for Angle relationship 3 in Experiment 1:

Consecutive interior angles:

When two parallel lines are crossed by a transversal, the two consecutive interior angles, inside the parallel lines and on the same side of the transversal, are supplementary (add to 180°), as in these diagrams.

Instruction for Angle relationship 3 in Experiment 2:

Co-interior angles:

When two parallel lines are crossed by a transversal, the two angles which are between the parallel lines and on the same side of the transversal add to 180°.

Second, more diagram examples for each angle relationship were added in the initial instruction to assist in students' understanding of the three angle relationships. Third, in an attempt to create a more sensitive test and to reduce the possibility of ceiling effects, the time allowed to answer each test question was shortened from 120 seconds to 60 seconds.

Students were tested individually, with each student being withdrawn from class for approximately 30 minutes. The experiment began with an initial instruction phase, identical for both groups. This phase was followed by an acquisition phase involving study with tracing or without tracing worked examples. The experiment concluded with a test phase of six questions. Each test question was followed by a test difficulty rating. The complete materials for both conditions are given in Appendix 2.

***Initial instruction phase*.** Students had 5 minutes to study the three angle relationships involving parallel lines, including:

1. Vertical angles are equal.
2. Corresponding angles are equal.
3. The sum of co-interior angles is 180°.

For each angle relationship, instruction was provided, which included a short text providing its definition, diagrams displaying the locations of the specific angles, and an example demonstrating how to use this angle relationship to solve a problem.

***Acquisition phase*.** All participants in the two conditions were then shown two worked examples applying the three angle relationships to find a missing angle. In the worked examples for the tracing group, every solution step was followed by instructions in brackets on tracing. Students were given 2 minutes to read and try to understand the solution steps, while using their index finger of their writing hand to trace out the diagram following the instructions. Students in the non-tracing condition were instructed to read and try to understand the solution steps for 2 minutes, with their hands placed on their laps.

Each worked example was paired with a similar practice problem, with a maximum of 2 minutes to solve the problem. Students who provided an incorrect answer were asked to try again within the 2-minute time limit. Students who could not work out the correct answer when the time was expended were stopped. They were required to study the worked example again and then went back to solve the practice problem until the correct answer was attained.

Test phase. The test phase consisted of two basic questions, with similar diagrams and similar solution steps to the worked examples but with different numbers, and four advanced questions, which differed from the worked examples with moderate variations in diagrams and the sequence of solution steps. Students had up to 1 minute to find a solution for each question.

Test item difficulty self-reports. After each test question, students were immediately asked to rate the difficulty of the question they had just attempted as an indication of intrinsic cognitive load. This 5-point subjective rating scale was identical to the one used in Experiment 1.

Results

The variables under analysis were number of correct answers, number of errors, total time for solution to practice problems at the acquisition phase, and number of correct answers, number of errors, total time for solution to test questions, and ratings of test item difficulty at the test phase. Means and standard deviations are provided in Table 5.1.

Table 5.1

Means and (Standard Deviations in Parentheses) for Acquisition Phase Number of Correct Answers, Number of Errors, Time for Solution (Seconds), and Test Phase Number of Correct Answers, Number of Errors, Time for Solution (Seconds) and Ratings of Test Difficulty

Variate	Non-tracing	Tracing
Acquisition Phase		
Number of correct answers	1.90 (.30)	1.90 (.30)
Number of errors	.33 (.58)	.14 (.36)
Time for solution	102.43 (49.50)	100.76 (53.74)
Test Phase		
Number of correct answers	2.76 (1.67)	4.52 (1.66)
Number of errors	1.33 (1.15)	0.43 (0.60)
Time for solution	316.05 (47.54)	258.05 (56.61)
Test difficulty	3.15 (0.65)	2.44 (0.50)

Acquisition phase. Due to non-normal distributions of the data across both conditions as indicated by the Shapiro-Wilks test, a Mann-Whitney test was used to analyze number of errors. The mean rank of the tracing condition (Mean rank = 19.93) was not statistically different to that of the non-tracing condition (Mean rank = 23.07), U = 187.50, p = .346, d = -.36. The difference between the tracing condition's time for solution (M = 100.76, SD = 53.74) and that of the non-tracing condition (M = 102.43, SD = 49.50) was also not statistically reliable, $t(40)$ = -.11, p = .917, d = -.03. As for number of correct solutions across practice questions, the identical performance of the two groups prevented analysis of this variable.

Test phase. Due to non-normal distributions of the data across both conditions as indicated by the Shapiro-Wilks test, a Mann-Whitney test was used to analyze number of errors, time for solution, and number of correct answers. For number of errors made across the test, the mean rank of the tracing condition (Mean rank = 16.00) was lower than that of the non-tracing condition (Mean rank = 27.00), $U = 105.00$, $p = .002$, $d = -1.07$. As for time for solution, the mean rank of the tracing condition (Mean rank = 15.50) was lower than that of the non-tracing condition (Mean rank = 27.50), $U = 94.50$, $p = .001$, $d = -1.10$. For number of test questions correctly answered, the mean rank of the tracing condition (Mean rank = 27.36) was higher than that of the non-tracing condition (Mean rank = 15.64), $U = 97.50$, $p = .001$, $d = 1.07$. Lastly, on the overall ratings of test item difficulty, the difference between the tracing condition ($M = 2.44$, $SD = 0.50$) and the non-tracing condition ($M = 3.15$, $SD = 0.65$) was also statistically significant, $t(40) = -3.97$, $p < .001$, $d = -1.23$.

Discussion

Informed by the initial findings of Experiment 1, Experiment 2 modified participant recruitment and test materials in order to generate a more sensitive test of hypotheses. In order to eliminate ceiling effects, which occurred in Experiment 1, a careful consideration of the match between experimental materials and participants was undertaken. As a result, younger participants were recruited and instructional materials were accordingly modified to align with their literacy level. Moreover, more difficult test questions were generated, as another method to reduce the possibility of ceiling effects. The procedure of Experiment 2 was otherwise the same as that of Experiment 1. It was hypothesized that the tracing group would perform better in the posttest and would consider the test questions less difficult, compared with the non-tracing group.

Results supported the hypotheses: the tracing condition significantly outperformed the non-tracing condition across a range of variates. While there were no statistically reliable differences between conditions on acquisition phase variates, in the subsequent test, students who traced worked examples during instruction solved more test problems correctly, made fewer errors, and solved problems more quickly. Students in the tracing condition also rated the test items as less difficult. The better test performance in combination with the lower level of test difficulty indicate that students in the tracing group constructed better problem solving schemas from the instructional materials to handle the test questions with lower cognitive demand, compared with their counterparts in the non-tracing group. The significant advantages of the tracing condition over the non-tracing condition strengthen the argument that tracing out elements of worked examples reduces intrinsic cognitive load, facilitating schema construction and/or schema automation over and above the typical benefits of learning from studying worked examples (Cooper & Sweller, 1987; Sweller & Cooper, 1985).

A key finding of Experiment 2 is the success of using the modified self-reported rating scale of perceived test difficulty to detect differences in intrinsic cognitive load. While most cognitive load theory-based studies have repeatedly demonstrated the reliability and the sensitivity of the rating scales of perceived difficulty or invested mental effort in studies involving adult participants, the present study's findings provide initial evidence for the efficacy of a graphical rating scale tailored for younger participants.

The strong tracing effect revealed in Experiment 2 indicates that tracing out worked examples can significantly enhance performance in the subsequent test in terms of accuracy, error rates, and time for solution. In order to test the generalizability of the findings, the same hypotheses were tested again in the next experiment, using a different mathematics topic.

Chapter Six: Experiment 3

Experiment 2 demonstrated that the basic worked example effect could be enhanced when students were required to trace the components of worked examples with their index finger. Students in the tracing condition not only performed better than those in the non-tracing group across different aspects of test performance, including number of test questions correctly answered, error rate and time for solution, but also considered the test items less cognitively demanding. The results indicate that tracing elements of worked examples while studying facilitates schema construction effectively and efficiently.

In order to explore the generalizability of the tracing effect obtained from Experiments 1 and 2, Experiment 3 was designed to test the research hypotheses with a different mathematics topic. In the previous two experiments, instructional materials on angle relationships involving parallel lines had been successfully used to generate the tracing effect. In Experiment 3, the experimental materials were redesigned to instruct properties of a triangle, which, according to the New South Wales mathematics syllabus, are scheduled for students at the late Stage 4 (i.e., Year 8). Since learning from studying worked examples is especially beneficial for novices, to ensure that participants in this experiment were novices with respect to this given mathematics topic, late Year 6 and early Year 7 students were recruited.

Given the previous success in Experiments 1 and 2 in generating the tracing effect when learning from complex mathematics materials, it was predicted that a positive effect on learning of tracing worked examples would again be obtained with this different mathematics topic. It was hypothesized that students in the tracing condition would demonstrate better average test performance, as measured by test questions correctly answered, error rate, and solution time, and lower levels of intrinsic cognitive load indicated by ratings of test item difficulty, compared with students in the non-tracing condition.

Method

Participants. 52 Year 6 and Year 7 students aged between 11 and 13 years old (*M* = 12.04, *SD* = .59) from two independent boys' schools in Sydney, Australia, voluntarily participated in this experiment. Participants were novices with respect to the properties of a triangle in the instructional materials. They were randomly assigned to the tracing or the non-tracing condition.

Materials and procedure. Students were tested individually, with each student being withdrawn from class for approximately 20 minutes. The experiment began with an initial instruction phase, identical for both groups. This phase was followed by an acquisition phase involving study with or without tracing elements of two worked examples. The experiment concluded with a test phase of six questions. Each test question was followed by a test difficulty rating. The complete materials for both conditions are given in Appendix 3.

***Initial instruction phase*.** The materials used in this phase consisted of two pages of initial instruction about two angle relationships involving a triangle. Students had 2 minutes to study the two angle relationships, including:

1. Vertical angles are equal.
2. Any exterior angle equals the sum of the two interior opposite angles.

For each angle relationship, instruction was provided, which included a short text providing its definition, diagrams displaying the locations of the specific angles, and an example demonstrating how to use this angle relationship to solve a problem.

***Acquisition phase*.** All participants were then shown two worked examples applying the two angle relationships to find a missing angle. In the worked examples for the tracing group, every solution step was followed by instructions in brackets on tracing. Students in the tracing condition were given 2 minutes to read and try to understand the solution steps, while using their index finger of their writing hand to trace out the diagram following the instructions. Students in the non-tracing condition were instructed to read and try to understand the solution steps for 2 minutes, with their hands placed on their laps.

Each worked example was paired with a similar practice problem, with a maximum of 2 minutes to solve the problem. Students who provided an incorrect answer were asked to try again within the 2-minute time limit. Students who could not solve the correct answer within the time limit were stopped. They were required to study the worked example again and then went back to solve the practice problem until the correct answer was attained.

As with the materials used in Experiments 1 and 2, the materials were designed in accordance with the principles of instructional design previously generated by cognitive load theory to reduce extraneous cognitive load. First, the diagrams and the associated text were physically integrated to avoid split attention. Second, arrows and color coding were used to link the associated information in the text and the diagram to ensure students correctly match the information from the two types of resources. Third, to reduce unnecessary mental burden and potential sources of calculation error, the numbers used in the materials were multiples of 5 or 10.

***Test phase*.** The test phase consisted of two basic questions, with similar diagrams and similar solution steps to the worked examples but with different numbers, and four advanced questions, which differed from the worked examples with moderate variations in diagrams and the sequence of solution steps. Students had up to 1 minute to find a solution for each question.

Test item difficulty self-reports. After each test question, students were immediately asked to rate the difficulty of the question they had just attempted as a measure of intrinsic cognitive load. This 5-point subjective rating scale was identical to the one used in Experiments 1 and 2.

Results

The variables under analysis were number of correct answers, number of errors, total time for solution to practice problems at the acquisition phase, and number of correct answers, number of errors, total time for solution to test questions, and ratings of test item difficulty at the test phase. Means and standard deviations are provided in Table 6.1.

Table 6.1

Means and (Standard Deviations in Parentheses) for Acquisition Phase Number of Correct Answers, Number of Errors, Time for Solution (Seconds), and Test Phase Number of Correct Answers, Number of Errors, Time for Solution (Seconds) and Ratings of Test Difficulty

Variate	Non-tracing	Tracing
Acquisition Phase		
Number of correct answers	2 (0)	1.96 (.20)
Number of errors	.19 (.57)	0 (0)
Time for solution	28.92 (11.88)	33.42 (19.69)
Test Phase		
Number of correct answers	3.04 (1.11)	3.92 (1.16)
Number of errors	3.15 (2.48)	0.73 (0.72)
Time for solution	258.65 (31.79)	248.35 (31.37)
Test difficulty	2.98 (0.63)	3.12 (0.40)

Acquisition phase. Floor effects on number of errors precluded analysis of this variate; no students in the tracing condition made any errors, and only 3 students in the non-tracing condition made errors. For number of correct answers, the mean rank of the tracing condition (Mean rank = 26.00) did not statistically differ from that of the non-tracing condition (Mean rank = 27.00), $U = 325.00$, $p = 1.000$, $d = -.28$. Because of skewed distributions, a Mann-Whitney test was used to analyze time for solution; no statistically significant difference was found between the tracing condition (Mean rank = 26.77) and the non-tracing condition (Mean rank = 26.23) on this variate, $U = 331.00$, $p = .902$, $d = .04$. Ceiling effects on number of correct answers precluded analysis of this variate; all students in the non-tracing condition correctly answered both practice problems, and all but one student in the tracing condition correctly answered both practice problems.

Test phase. Mann-Whitney tests were used to analyze number of errors, time for solution, number of correct answers, and the ratings of test difficulty, due to skewed distributions. The tracing group (Mean rank = 31.90) correctly answered more test questions than the non-tracing group (Mean rank = 21.10), U = 197.50, p = .007, d = .80. The tracing group (Mean rank = 17.94) made significantly fewer errors than the non-tracing group (Mean rank = 35.06), U = 115.50, p < .001, d = -1.42. However, no significant difference between the tracing (Mean rank = 23.71) and the non-tracing groups (Mean rank = 29.29) on time for solution was obtained, U = 265.50, p = .188, d = -.37. Likewise, for the overall ratings of test item difficulty, the difference between the tracing condition (Mean rank = 28.21) and the non-tracing condition (Mean rank = 24.79) was also not statistically significant, U = 293.50, p = .418, d = .22.

Discussion

The purpose of Experiment 3 was to test whether the results of Experiments 1 and 2 could be generalized to a different mathematics topic. In Experiment 3, the same research hypotheses were examined with instructional materials about properties of a triangle. According to the New South Wales mathematics syllabus, this mathematics topic is scheduled for Year 8 students, so late Year 6 and early Year 7 students who had not yet learned this specific topic at school were recruited. If the findings from the previous two experiments were generalizable, the same positive tracing effect would be obtained; the group of novices who studied worked examples with tracing would have superior learning outcomes and experience lower levels of test difficulty, compared with the group who simply studied worked examples.

Results supported some but not all hypotheses; the tracing condition performed better at the posttest, attaining more correct answers and making fewer errors than the non-tracing condition. With regard to time for test question solution and cognitive load, the tracing condition did not spend less time for the test and did not consider the test less cognitively demanding as expected. However, even though the two groups of students experienced about the same level of test difficulty and solved the problems with about the same amount of time, the tracing group managed to outperform the non-tracing condition while making fewer errors. This indicates that students in the tracing condition were more capable of generating correct solution steps based on what they had learned during the acquisition phase. In sum, the results again provide evidence for the effectiveness of tracing while studying worked examples, which supports more effective problem solving than simply studying worked examples.

Given the two mathematics topics used across Experiments 1 to 3 are both categorized to the strand of space and geometry in the New South Wales mathematics syllabus, it is reasonable to say that the results of Experiment 3 suggest that the positive effects on learning of tracing worked examples obtained in Experiments 1 and 2 could be generalized to other visuo-spatial-based mathematics subjects. This finding is not only consistent with the finding that the presence of the hands affects visual processing of stimuli in the perihand area (for a review, see Brockmole, Davoli, Abrams, & Witt, 2013) but also supportive of the idea that haptic information and visuo-spatial information are linked within the same processing channel and presumably share a common representation. Accordingly, it can be argued that incorporating tracing movements into the instruction of highly visuo-spatial mathematics topics should result in better learning outcomes for novices. However, it does not necessarily mean that tracing worked examples only benefits visuo-spatial subjects. Whether the tracing effect can be extended to other mathematics topics with fewer visuo-spatial components is certainly worth further investigation.

Overall, Experiment 3 replicates and extends findings from Experiments 1 and 2 that students learn better while tracing components of worked examples than simply studying worked examples. Since the haptic modality is a composite of the tactile and the kinesthetic modalities, and active touch plays an essential role in haptic perception, in the next experiment, the effects on learning of tracing worked examples with and without the tactile sense are explored.

Chapter Seven: Experiment 4

The results of Experiment 3 indicate that the tracing effect obtained from Experiments 1 and 2 can be extended to a different mathematics topic. After studying and tracing worked examples instructing properties of a triangle at the acquisition phase, students in the tracing condition correctly answered more questions and made fewer errors at the test phase than those in the non-tracing condition. Using tracing during learning processes apparently assists students to construct more effective schemas.

Following the establishment of the beneficial effects of incorporating the haptic modality into worked examples-based instruction, Experiment 4 was designed to further investigate the tracing instructional technique. As previously mentioned in the literature review, the haptic perceptual system consists of two subsystems, cutaneous (meaning "of or relating to the skin"; for the purpose of this thesis, "tactile", meaning "of or connected with the sense of touch" is used in preference) and kinesthetic (Lederman & Klatzky, 2009). In a learning context, sometimes students will spontaneously hold a pointing finger making tracing movements in the air of new words or graphic shapes which they are trying to learn. In that case, students add haptic input coming from the kinesthetic modality only into their learning processes. In contrast, when the participants in Experiments 1 to 3 were instructed to put their index finger on the piece of paper and trace out the worked examples on it, sensory input from both the tactile and the kinesthetic modalities was received and incorporated with visual input into a representation initially held in working memory, then encoded into long-term memory. This raises the question of whether multiple non-visual sensory modalities are best used to maximize learning from worked examples (i.e., tracing with the finger on the paper), or whether similar results would be obtained if only one non-visual sensory modality was coupled with visual input (e.g., tracing with the finger in the air just above a worked example). This latter manner of embodied interaction with a worked example could be expected to enhance learning given the focusing of attention around perihand space (Abrams et al., 2008; Cosman & Vecera, 2010; Reed et al., 2006, 2010). However, since haptic perception heavily relies on active touch (Gibson, 1962; Klatzky & Lederman, 2003), it is assumed that learning will be enhanced to a greater extent when both tactile and kinesthetic representations of to-be-learned information are activated and integrated in working memory along with visual input. Experiment 4 tested hypothesized gradients across experimental conditions, predicting that students who traced on the surface of instructional materials (i.e., affecting visual, kinesthetic and tactile working memory channels) would outperform those who traced in the air above the materials (i.e., affecting visual and kinesthetic working memory channels), who in turn would outperform those who simply studied worked examples (i.e., visual working memory channel only). A gradient in average test item difficulty ratings was also hypothesized, predicting that students who traced on the surface of instructional materials would report lower levels of test difficulty than those who traced in the air above the materials, who in turn would report lower levels of test difficulty than those who simply studied worked examples.

Method

Participants. Participants consisted of 72 Year 5 students, including 56 boys and 16 girls, from 2 independent schools in Sydney, Australia. All participants participated voluntarily, and were aged between 9 and 11 years old (M = 9.94, SD = .33). Participants were novices with respect to the three angle relationships in the instructional materials. They were randomly assigned to the tracing on the paper (tracing with touch) condition, the tracing above the paper (tracing without touch) condition, or the non-tracing condition.

Materials and procedure. The same instructional materials to those used in Experiment 2 were used. However, in order to create a more sensitive test, two more test questions were added to the original six test questions. The original test consisted of two basic questions and four advanced questions. The two additional questions were slightly harder than the four original advanced questions. In one additional question, one of the corresponding angles was divided into two adjacent angles, so it was not as easy for students to immediately identify the pair of corresponding angles. In the other additional question, one of the co-interior angles was divided into two adjacent angles. It was assumed that students who could solve the higher-transfer test questions were more likely to have constructed superior schemas during learning. The current test with advanced questions at different difficulty levels should be more sensitive to reflect the differences in students' learning outcomes across the hypothesized gradients.

Students were individually tested, with each student being withdrawn from class for approximately 35 minutes. The experiment began with an initial instruction phase, identical for all groups. This phase was followed by an acquisition phase involving study with tracing worked examples on the paper, tracing worked examples above the paper, or without tracing. The experiment concluded with a test phase of eight questions. Each test question was followed by a test difficulty rating. The complete materials for all the three conditions are given in Appendix 4.

Initial instruction phase. Students had 5 minutes to study the three angle relationships involving parallel lines, including:

1. Vertical angles are equal.

2. Corresponding angles are equal.

3. The sum of co-interior angles is 180°.

For each angle relationship, instruction was provided, which included a short text providing its definition, diagrams displaying the locations of the specific angles, and an example demonstrating how to use this angle relationship to solve a problem.

Acquisition phase. All participants in the three conditions were then shown two worked examples applying the three angle relationships to find a missing angle. First, in the worked examples for the tracing on the paper group, every solution step was followed by instructions in brackets on tracing. Students were given 2 minutes to read and try to understand the solution steps, while putting their index finger of their writing hand on the paper to trace out the diagram following the instructions. Second, students in the tracing above the paper condition were also shown the worked examples with every solution step followed by instructions in brackets on tracing. They also had 2 minutes to read and try to understand the solution steps, but they were instructed to keep their index finger about 5 centimeters above the paper and trace out the diagram following the instructions without touching the paper. Lastly, students in the non-tracing condition were instructed to read and try to understand the solution steps for 2 minutes, with their hands placed on their laps.

Each worked example was paired with a similar practice problem, with a maximum of 2 minutes to solve the problem. Students who provided an incorrect answer were asked to try again within the 2-minute time limit. Students who could not solve the correct answer when the time was expended were stopped. They were required to study the worked example again and then went back to solve the practice problem until the correct answer was attained.

***Test phase*.** The test phase consisted of two basic questions, with similar diagrams and similar solution steps to the worked examples but with different numbers, and six advanced questions, which differed from the worked examples with moderate variations in diagrams and the sequence of solution steps. Students had up to 1 minute for each question.

Test item difficulty self-reports. After each test question, students were immediately asked to rate the difficulty of the question they had just attempted as an indication of intrinsic cognitive load. This 5-point subjective rating scale was identical to the one used across Experiments 1 to 3.

Data Analysis

When testing hypotheses with sequence order (i.e., condition 1 > condition 2 > condition 3, or vice versa), using statistics that incorporate information about the hypothetical rank order will typically result in higher power compared with conventional analysis of variance procedures (McKean, Naranjo, & Huitema, 2001). Given the clear hypotheses described above regarding expected gradients on variates across conditions, analyses consisted of bootstrapped estimates of Spearman's rank-order correlation coefficient between the independent variable and median scores for each condition on dependent variables under analysis. This method is robust for analyzing variances of experimental designs with an expected order of dependent variables (McKean et al., 2001), and has the benefit over alternative methods (e.g., Terpstra, 1952) of generating an effect size (Spearman's *r*) in addition to a *p* value. For consistency with analyses presented in previous chapters, values of Spearman's *r* presented below were accompanied by values of *d*, using the typical transformation for *r* to *d* (see Chapter 7 of Borenstein et al., 2009). Bootstrapped *p* values were one-sided given the directional hypotheses used in the current experiment.

Results

The variables under analysis were number of correct answers, number of errors, total time for solution to practice problems at the acquisition phase, and number of correct answers, number of errors, total time for solution to test questions, and ratings of test item difficulty at the test phase. Means and standard deviations are provided in Table 7.1.

Table 7.1

Means and (Standard Deviations in Parentheses) for Acquisition Phase Number of Correct Answers, Number of Errors, Time for Solution (Seconds), and Test Phase Number of Correct Answers, Number of Errors, Time for Solution (Seconds) and Ratings of Test Difficulty

Variate	Non-tracing	Tracing above the paper	Tracing on the paper
Acquisition Phase			
Number of correct answers	1.63 (.49)	1.63 (.65)	1.92 (.41)
Number of errors	0.46 (0.93)	0.08 (0.28)	0.08 (0.28)
Time for solution	110.58 (54.07)	126.00 (63.42)	90.38 (47.12)
Test Phase			
Number of correct answers	3.50 (2.04)	4.38 (1.93)	5.58 (1.06)
Number of errors	2.63 (3.20)	2.13 (2.89)	1.33 (1.31)
Time for solution	403.42 (54.26)	391.71 (61.86)	364.25 (54.68)
Test difficulty	3.42 (0.68)	3.16 (0.49)	3.01 (0.56)

Acquisition phase. In order to test the hypothetical sequence order of students' performance (tracing on the paper > tracing above the paper > non-tracing for number of correct answers; tracing on the paper < tracing above the paper < non-tracing for number of errors and time for solution), Spearman's rank-order correlation coefficient between experimental condition and the three variates from the acquisition phase was estimated. A statistically reliable gradient was found for number of errors, $r = -.24$, $p = .021$, $d = -.49$, but not time for solution, $r = -.15$, $p = .108$, $d = -.30$. The gradient for number of correct answers was also statistically reliable, $r = .30$, $p = .006$, $d = .62$.

Test phase. Spearman's rank-order correlation coefficient was also used to test hypothesized gradients between experimental condition and the four variates from the test phase (tracing on the paper > tracing above the paper > non-tracing for number of correct answers; tracing on the paper < tracing above the paper < non-tracing for number of errors, time for solution, and ratings of test item difficulty). The gradient for number of errors was not statistically reliable, $r = -.17$, $p = .076$, $d = -.34$. A statistically reliable gradient was found for time for solution, $r = -.28$, $p = .009$, $d = -.58$, and number of correct answers, $r = .43$, $p < .001$, $d = .95$. Likewise, the gradient in the overall ratings of test item difficulty was also significant, $r = -.27$, $p = .014$, $d = -.55$.

Discussion

Considering the haptic sensory modality consists of the tactile and the kinesthetic modalities, Experiment 4 was designed to further explore the tracing effect by examining whether tracing with and without the sense of touch would affect learning outcomes, compared with a control group relying on visual study only. It was hypothesized that, when students put their index finger on the paper and traced the worked examples on it, working memory resources from both the tactile and kinesthetic modalities would become active to be used along with vision-based learning processes. This expansion of available working memory for learning was expected to be reflected in relatively better test performance, and relatively lower ratings of test difficulty, reflecting better schema construction, compared with the other conditions. In contrast, students who kept their index finger above the paper and made tracing movements were hypothesized to incorporate kinesthetic input only with visual input in working memory, thus expanding working memory capacity available for learning but to a lesser extent. Students in the control condition who kept their hands on their laps without any movements were hypothesized to rely on visual working memory only to support learning. Based on previous research demonstrating that learning with input from multiple modalities results in better encoding and better retrieving of information (Ginns, 2005), it was predicted that students in the tracing on the paper condition, who learned with three types of inputs from the tactile, the kinesthetic and the visual modalities, would have the best performance at the posttest and report the lowest level of perceived test difficulty. Students in the non-tracing condition, learning with only visual input, would have the worst performance and report the highest level of perceived test difficulty. Students who traced in the air were expected to perform mid-way between these extremes, reflecting the partial expansion of working memory capacity available for learning through the kinesthetic channel, along with the focusing of visual attention on the instructional materials in perihand space.

Results supported most of the hypotheses presented above. First, during the acquisition phase, the hypothesized gradient was found for number of errors (tracing on the paper = tracing above the paper < non-tracing) and number of questions correctly answered (tracing on the paper > tracing above the paper > non-tracing), but not time for solution. Second, during the test phase, the hypothesized gradient was found for time for solution and ratings of test item difficulty (tracing on the paper < tracing above the paper < non-tracing) and number of questions correctly answered (tracing on the paper > tracing above the paper > non-tracing), but not for number of errors made.

From the perspective of cognitive load theory, when new information is encountered via more than one sensory format, cognitive load will be distributed among different information processors within working memory. Accordingly, more cognitive resources will be available to encode that information in long-term memory. Taken together, the results of Experiment 4 demonstrate that when instructional design of worked examples incorporates the haptic modality, the inclusion or exclusion of the tactile modality makes a significant difference in students' learning outcomes. These results are consistent with prior research investigating tracing for learning (e.g., Bara et al., 2004, 2007; Hulme et al., 1987), but extend this research by demonstrating the best learning outcomes result from simultaneous touch and movement while tracing compared with movement alone.

Chapter Eight: General Discussion

8.1 Summary of Key Findings

In many educational settings, most teaching and learning is accomplished via the visual and/or the auditory sensory modalities. Although the human brain has evolved to constantly receive multisensory stimulation in the real world, explicit use of modalities other than vision and audition is much less common. However, research on the modality effect (Ginns, 2005; Mousavi et al., 1995) has suggested that learning new information presented in formats across multiple sensory modalities can reduce cognitive load imposed on each processing channel, with the result that working memory available for learning may increase. Following the logic of the modality effect, using multiple sensory modalities to undertake a learning task is likely to yield improved learning outcomes. While advocacy for the educational use of the haptic modality—comprising the sense of touch (tactile modality), and the sense of the body moving in space (kinesthetic modality)—has existed for over a century (e.g., Montessori, 1914), cognitive load theory, as a major contemporary learning theory, has not yet considered using the haptic modality in active learning processes.

Evidence has shown that the capacity to point is a skill that emerges naturally at infancy (Liszkowski et al., 2012), and the associated use of a pointing finger for tracing has been demonstrated to enhance secondary knowledge learning such as letters (Hulme et al., 1987) and geometrical shape recognition (Kalenine et al., 2011). Based on the argument made by the recently upgraded cognitive load theory that biologically primary knowledge might support the acquisition of biologically secondary knowledge, this thesis evaluated a worked example-based instructional redesign, featuring the incorporation of haptic input from tracing and pointing movements with the visual study of worked examples. It was argued that tracing while studying worked examples would generate additional working memory capacity from the tactile and the kinesthetic modalities to support the construction of schemas and thus enhance learning, compared with simply studying worked examples. The hypotheses of the thesis were examined across a series of four experiments.

Experiment 1 investigated the impact on learning of using tracing during worked example-based learning. Students in the tracing condition were instructed to use their finger to trace elements of worked examples on angle relationships involving parallel lines; those in the non-tracing condition were instructed to study worked examples with their hands on their laps. It was argued that tracing while studying worked examples would recruit additional resources to support schema construction, resulting in enhanced test performance and reduced test difficulty, compared with simply studying worked examples. The argument was partially supported by the results, showing the tracing group correctly solved more practice problems at the acquisition phase and made fewer errors at the test phase. They also rated one of the advanced test questions as less difficult than the non-tracing group. These findings provided initial evidence for the prospective positive impacts on learning of tracing worked examples.

Experiment 2 was designed to again examine the differences in learning outcomes between the tracing and non-tracing groups with a better alignment of participants' prior knowledge and instructional materials. Younger participants and a more difficult test with harder questions and a shortened time limit were used to reduce chances of repeating the ceiling effect found on test questions correctly answered in Experiment 1. Experimental materials on angle relationships associated with parallel lines were modified to accommodate the literacy ability of younger students; otherwise, the experimental design was identical to Experiment 1. It was expected that significant differences between instruction with tracing and without tracing would be obtained with the experimental redesign. Results of Experiment 2 showed a strong tracing effect; although no statistically reliable differences between conditions were found on acquisition phase variates, the tracing condition significantly outperformed the non-tracing condition at the test phase with more questions correctly solved, fewer errors made and less time spent reaching correct solutions to questions. The test items were also rated as less difficult by the tracing condition. The superior test performance and the lower test difficulty ratings by the tracing condition were consistent with predictions that tracing while studying worked examples would support schema construction and consequently reduce intrinsic cognitive load at the test phase, enhancing the benefits of learning from simply studying worked examples.

In order to test the generalizability of the tracing effect observed in Experiment 2, Experiment 3 was designed to examine whether the tracing effect obtained from the previous experiments could be extended to a different mathematics topic and a different age group. Slightly older students were recruited and randomly assigned to the tracing or the non-tracing condition to study instructional materials on angle relationships of a triangle. If tracing could have generally beneficial effects on learning, statistically reliable differences in performance and test difficulty ratings between the tracing and the non-tracing conditions would be replicated in Experiment 3. Results showed that students in the tracing condition had better performance across some but not all variates. They attained more correct answers and made fewer errors than those in the non-tracing condition at the test phase. While there were no significant differences in time for solution and cognitive load ratings between conditions, the outperformance by the tracing group in terms of test accuracy rate and test error rate indicated a superior schema construction during the acquisition phase, supporting more effective problem solving.

Experiment 4 further investigated the effectiveness of instruction with tracing while including or excluding the sense of touch. Instructional materials on angle relationships involving parallel lines identical to Experiment 2 were used again. Two additional advanced test questions were added, in order to create a more sensitive test. The assumption underlying Experiment 4 was that the more working memory modalities were used during the acquisition phase, the more students' learning would be enhanced. Based on this assumption, it was predicted that the tracing on the paper group (learning with kinesthetic, tactile and visual inputs) would have the best learning outcomes, the non-tracing group (learning with visual input) have the lowest learning outcomes, and the tracing above the paper group (learning with kinesthetic and visual inputs) would perform in-between the other conditions. In addition, the tracing on the paper group would report the lowest level of test difficulty and the non-tracing group would report the highest level, with the tracing above the paper group in the middle. Results supported most of the hypotheses above. First, during the acquisition phase, the hypothesized gradient was found for number of errors (tracing on the paper = tracing above the paper < non-tracing) and number of questions correctly answered (tracing on the paper > tracing above the paper > non-tracing). Second, during the test phase, the hypothesized gradient was found for time for solution and ratings of test item difficulty (tracing on the paper < tracing above the paper < non-tracing) and number of questions correctly answered (tracing on the paper > tracing above the paper > non-tracing). The findings of Experiment 4 demonstrated that when instructional design of worked examples incorporates tracing movements, the inclusion of the touch sense further enhances students' learning.

8.2 Theoretical and Methodological Implications

The series of experiments built on cognitive load theory as the primary theoretical framework, and the results not only support the propositions of the theory but also go beyond to expand its scope. The primary contribution of the thesis is the identification of pointing and tracing movements as forms of biologically primary knowledge that support the construction of biologically secondary knowledge (e.g., geometry), supporting conjectures made in the recent "evolutionary upgrade" (Paas & Sweller, 2012) of cognitive load theory. The skill of moving a pointing finger naturally emerges at infancy, without explicit instruction, and has been used in daily life to support cognitive activity such as communication and counting. This research manifests that such natural and effortless hand movements can be used deliberately and consciously to facilitate learning in a formal educational context.

Second, the results suggest that the worked example effect can be enhanced by incorporating tracing instructions. Suitably designed worked examples have been widely recognized as an effective instructional technique for novices, as they direct cognitive resources to schema construction, and reduce extraneous cognitive load. Recently, cognitive load researchers have started to investigate how the worked example design can be optimized, such as through increasing germane cognitive load in learning from worked examples (Paas & Van Gog, 2006). A promising method to enhance the worked example effect has been demonstrated across Experiments 1 to 4 in the current thesis; students who traced worked examples generally had better test performance and reported lower levels of test difficulty than those who simply studied worked examples. It is argued that adding tracing instructions into worked examples could help students construct better schemas, which would be more easily retrieved and applied to solve test questions; hence, students in the tracing condition would experience lower levels of intrinsic cognitive load, as indexed by difficulty ratings, and show enhanced performance at the test phase.

Third, the results support and extend the modality effect (i.e., the use of different sensory modes for presentation of new information makes more cognitive resources available for learning; Ginns, 2005; Mousavi et al., 1995; Tindall-Ford et al., 1997). In particular, Experiment 4 demonstrated that the greater the number of working memory modalities activated during learning, the better the problem solving schemas constructed. When the to-be-learned information was encoded through three modalities (i.e., visual, tactile and kinesthetic), students' learning was enhanced more than when information was encoded through two modalities (i.e., visual and kinesthetic), which in turn was more effective than encoding through one modality (i.e., visual) only. In addition, while previous studies on the modality effect have focused on the visual and the auditory modalities, the present research provides initial evidence for the effectiveness of using the haptic modality under the cognitive load theory framework. It should be noted that the tracing effect and the classical modality effect share the same idea of using multiple modalities to make an optimal use of the available working memory resources; however, hypothesizing underpinning the tracing effect holds that incorporating haptic information into learning processes could enhance visual processing and accordingly supports construction of better quality schemas, while the modality effect holds that a potential overload of one processing channel could be avoided by dividing information across multiple modalities.

Fourth, and related to the previous point, when the presented information involves multiple modalities and/or multiple media, it is important to guide students to select information for processing, which could effectively reduce extraneous cognitive load and improve learning (de Koning et al., 2009). Previous studies have found that putting the hands near the to-be-learned information prioritizes, increases and prolongs the allocation of attention, leading to a deeper and detail-oriented visual processing of that information (Brockmole et al., 2013), and that it is more difficult to shift attention away from the tactile modality than the visual or the auditory modality (Spence et al., 2001). The results of the present research extend these findings into the field of instructional design, suggesting that using a finger to point and touch could serve as a powerful attentional cue, effectively drawing students' attention to essential elements of instructional materials.

Fifth, the present thesis includes a methodological innovation in measuring cognitive load. The pictorial 5-point self-report rating scale designed for the present experiments, based on the Faces Pain Scale—Revised (Hicks et al., 2001), was found in Experiments 2 and 4 to be able to detect hypothesized variations in young students' perceptions of test difficulty across conditions. These group differences were held to represent differences in intrinsic cognitive load that students experienced while solving problems. As the majority of studies based on cognitive load theory have recruited adults as participants, these results signify a promising innovation for unobtrusively measuring intrinsic cognitive load with younger participants, for whom notions of "mental effort" (cf. Van Loon-Hillen et al., 2012) may be relatively difficult to comprehend.

Lastly, while the tracing method has been repeatedly demonstrated to benefit learning of biologically secondary knowledge in the form of letters (e.g., Hulme et al., 1987) and geometric forms (Kalenine et al., 2011) in young children, the results of the present thesis extend this line of research by demonstrating the benefits of tracing across substantially more advanced topics such as mathematical geometry rules. Along with recent research (Macken & Ginns, in press) demonstrating the potential for tracing to enhance learning from expository text and diagrams on the structure and function of the human heart, it appears that tracing may have substantial potential for enhancing learning across a range of subjects and age ranges.

8.3 Educational Implications

The primary educational contribution of the present thesis is its demonstration of a simple, easily implemented and effective modification to worked example study instructions. It was found that students learned better when learning materials include instructions to trace out elements of worked examples. This result indicates that instructing students to trace instructional materials during learning processes has positive effects on cognition and learning. Over and above general benefits for learning and problem solving, the tracing instructions used in the present experiments allow students to clarify the meanings of specific solution steps they have just read. For instance, after reading “When two lines cross, vertical angles are equal, so this angle is 50°. [Trace out the two vertical angles with your finger]”, if students can correctly trace out the angles to confirm their understanding of the solution step, they are more likely to correctly encode the information and construct correct problem solving schemas. This is similar to the idea of “grounding” held by embodied cognition (Barsalou, 2008, 2010). The information in the text is grounded in the corresponding elements in the diagrams through the movements of tracing; in other words, the tracing movements connect abstract mathematics concepts to something concrete and touchable. In addition, tracing may also allow students to have physical experiences during the learning of abstract mathematics concepts, creating additional embodied representations for mathematics problem solving. Such bodily and procedural representations can complement declarative understanding of mathematics concepts to support abstract mathematical thinking and learning (Cook, Duffy, & Fenn, 2013).

Taken together, it is clear that instructing students to use a pointing finger to trace on the surface of learning materials offers teachers an embodied instructional technique for improving their students' learning from conventional paper-based instructional materials. Teachers can incorporate hand movements into their instructional design by encouraging students to point, touch, and trace learning materials. Since electronic devices such as interactive white boards and tablet-based computers are increasingly used in classrooms, the tracing effect may also inform teachers in creating different haptic learning experiences for their students. For example, the large screen of an interactive white board can allow students to produce bigger scales of tracing movements or allow multiple students to collaboratively work on it. The small screen of a tablet, in contrast, is more suitable for an individual learning space, but the big selection of applications for tablets may be more convenient for teachers to choose or design learning activities incorporating haptic input for different subjects. The responsive touch screens of such electronic devices apparently make learning by tracing and touching more dynamic, which may offer a lot of engaging activities for technology-savvy students. On the other hand, for students who prefer paper-based materials, the tracing method obviously creates a static interface for them to interact with. That is to say, with a pointing finger, students are equipped with a portable learning tool, which can turn any surfaces of learning materials into a “touch screen”.

8.4 Limitations of the Present Study and Suggestions for Future Research

The present findings have some limitations which can inform future investigations of tracing effects. First, the present findings are limited to no retention interval, as the posttest was conducted immediately after the acquisition phase. The immediate posttest performance could be influenced by transient factors such as fatigue, boredom, motivation or excitement, which may not necessarily indicate any change in long-term memory. One strategy to assess the amount of learning students really acquire from instruction is to conduct delayed tests (or retention tests), allowing a proper retention interval to dissipate the influences of transient factors (Dubrowski, 2005; Dubrowski, Carnahan, & Reznick, 2010). Previous studies have shown that producing gestures during encoding results in better memory retention (e.g., Cook et al., 2008, 2010; Stevanoni & Salmon, 2005). Recently, Cook et al. (2013) found that students who observed gestures along with speech outperformed those who received speech only at both the immediate test and the delayed test after a 24-hour interval. Interestingly, the benefit of gestures for the “speech with gesture” group was larger on the delayed test than the immediate test, suggesting gestures may consolidate or even increase learning during the intervening period. If tracing movements have the same effects on learning as the co-speech gestures in the previous studies mentioned above, it can be hypothesized that tracing worked examples may contribute to enhanced learning over time. If the hypothesis holds true, better test performance in the tracing condition than the non-tracing condition will also be observed on a delayed test. Furthermore, an investigation of the tracing effect across varying retention intervals would also be a useful extension of the present research, as Hulme (1979) speculated that more noticeable tracing effects might emerge with time considering the durability of motor representations.

Second, in the experiments presented in the thesis, hypotheses regarding intrinsic cognitive load were tested using self-report scales. While such measures are widely used in studies generated from cognitive load theory, and results accorded with hypotheses, future investigations should continue to gather process data to strengthen the case for a cognitive load interpretation of performance data. For example, future studies might supplement self-reports of cognitive load with eye-tracking data (Van Gog, Kester, Nievelstein, Giesbers & Paas, 2009; Van Gog & Scheiter, 2010). While self-ratings mainly measure overall perceived cognitive load, tracking eye movements can directly measure cognitive load imposed by particular cognitive processes. It has been shown that as processing demands increase, pupil dilation (e.g., Van Gerven, Paas, Van Merriënboer, & Schmidt, 2004), and fixation duration (e.g., Underwood, Jebbett, & Roberts, 2004) increase, which suggests that collecting both eye movement data and self-rating data at the test phase may provide more valid information to detect variations of intrinsic cognitive load. If certain instructional materials allow students to construct better schemas, which could be more easily retrieved and applied to problem solving, it is expected that students who report lower levels of overall cognitive load will also have a lower mean fixation duration at the test phase, indicating lower levels of intrinsic cognitive load. These students are also more likely to demonstrate better test performance. An alternative method to supplement self-rating data is using a popular neuroimaging technique—electroencephalography (EEG)—

to collect brain activity data. Such measurements provide a continuous index reflecting individuals' information processing conditions responding to changing levels of cognitive stimuli (Klimesch, 1999), which could serve as an indication of fluctuations in experienced cognitive load. Evidence has shown that alpha and theta brainwave is related to cognitive load (e.g., Gevins & Smith, 2000; Gevins, Smith, McEvoy, & Yu, 1997; Sterman, Mann, Kaiser, & Suyenobu, 1994); as cognitive load increases, alpha activity decreases and theta activity increases. Thus, if higher alpha activity and lower theta activity are indicated by EEG, in combination with lower levels of test difficulty self-ratings and better performance at the test phase in the tracing condition, the interpretation of tracing worked examples facilitating schema construction and/or schema automation to reduce intrinsic cognitive load during problem solving would be further supported.

Third, the present series of experiments did not consider the role of any individual differences which might moderate the effectiveness of tracing instructions (Cronbach & Snow, 1977). For example, a large body of research on the expertise reversal effect has suggested that instructional designs which are effective for novices—such as those recruited in the present experiments—may decline in effectiveness as prior knowledge increases (Kalyuga, 2007). A relevant study by Homer and Plass (2010) found that iconic representations in science visualizations were more effective for students with lower prior knowledge than those with higher prior knowledge. Similarly, Petersen and McNeil (2013) found that using perceptually rich concrete objects facilitated students' understanding of mathematics abstract concepts when they had lower knowledge but hindered performance when they had higher knowledge. However, Goldstone and Sakamoto (2003) offered different conclusions; they found that students with higher ability were positively affected by concrete and clearly pictorial materials, and an opposite effect was found for students with lower ability. Recently, Post, Van Gog, Paas, and Zwaan (2013) also found that asking students with lower language ability to simultaneously observe and make gestures did not lighten cognitive load and facilitate the acquisition of grammatical rules as expected. Contrarily, the gesturing group had a worse performance than the non-gesturing group. These studies suggest that interactions between perceptual richness and prior domain knowledge may be complicated. Since tracing mathematics worked examples can be considered as a method for perceptually enriching the understanding of abstract concepts, whether or the extent to which the effectiveness of tracing changes with prior knowledge would be worthy of further investigation.

Another potential aptitude-treatment interaction might relate to spatial ability, which has been found to be positively correlated with mathematics tasks, especially when dealing with geometry and complex problems (Jones & Bills, 1998; Van Garderen, 2006; Wheatley, 1990). After conducting a meta-analysis focusing on the role of spatial ability in learning with visualizations, Höffler (2010) found that students with lower spatial ability were superior to those with higher spatial ability when learning with dynamic visualizations. In contrast, students with higher spatial ability benefited more from learning with non-dynamic visualizations. One explanation for the results would be that dynamic animations help to create mental models for low spatial ability students, while high spatial ability students are capable to build mental models on their own without the need of extra support. On this account, if tracing effects operate substantially through their effects on processing in the visuo-spatial sketchpad (cf. Baddeley, 2012), contributing to the building of mental models, then students higher in spatial ability might find instructions to trace relatively redundant. Their performance may even be hindered by the tracing instructional technique.

One consideration that should also be noted is that, while the effects of tracing were strong for the inherently visuo-spatial-based mathematics materials used in the thesis, it remains to be seen how tracing instructions might be incorporated into topics that are less obviously visuo-spatial in nature. If future evidence can support that tracing also benefits learning from less- or non-visuo-spatial materials, it could be argued that tracing exerts its influences on cognitive processes beyond visuo-spatial processing. Instructional design elements used for signaling (de Koning et al., 2009), such as arrows and call-out boxes, may be candidates for tracing in instructional materials that are otherwise "low" in visuo-spatial content compared with the geometrical materials used in the present thesis.

Research on effective sequencing of instructions involving tracing would be worthwhile. For example, in describing an instructional sequence for sandpaper letters, Montessori (1912) noted "the children, as soon as have become at all expert in this tracing of the letters, take great pleasure in repeating it *with closed eyes*, letting the sandpaper lead them in following the form which they do not see" (p. 276; italics in original). Such a sequence has considerable parallels with instructions used in generating the imagination effect (Cooper et al., 2001; Ginns et al., 2003), where students first construct a schema through studying materials, then partially or fully automate the schema by closing the eyes and imagining the instructions. In this manner, students' new learning will be further enhanced. However, it should be emphasized that the effectiveness of imagination instructions depends on sufficient schema construction in the first instance. If students are not ready to imagine the newly learned information, imagination instructions may even be harmful to learning; for example, Ginns et al. (2003) demonstrated that students who studied then imagined worked examples learned better than those who imagined then studied. It may be interesting for future research to further test the sequence of studying and imagining interacting with the tracing effect. As tracing during learning enhances schema construction, a compensating effect of tracing instructions for students in the imagining then studying condition may be expected. That is to say, presumably the differences in performance between the studying then imagining condition and the imagining then studying condition might be diminished when involving tracing instructions, compared with when no tracing instructions are involved.

Lastly, it would also be interesting to investigate whether the interacting effect of tracing and imagining instructions will vary while tracing on different types of material texture, for instance, tracing on normal paper as opposed to sandpaper as used in Montessori education. Evidence has shown a link between visual and tactile areas in the brain; touch sensations can aid visual processing, as the brain not only remembers the appearance of an object but also remembers the feeling while touching it (Meyer, Kaplan, Essex, Damasio, & Damasio, 2011). If the diagrams of worked examples used in the present series of experiments were cut out in sandpaper and glued to normal paper with solution steps, students would have a distinct tactile sense while tracing and encoding the information, which might serve as a distinct tactile memory trace to represent the information in working memory during imagining. It is reasonable to hypothesize that while students in the tracing sandpaper condition close their eyes and trace the sandpaper following the imagining instructions, they will be led by the distinct tactile and kinesthetic senses to construct better mental representations, compared with the students in the tracing normal paper condition.

8.5 Conclusions

Without explicit instruction and a sufficient amount of effort, it is almost impossible to acquire biologically secondary knowledge, but humans have evolved to effortlessly acquire biologically primary knowledge that may support biologically secondary knowledge acquisition. The present thesis argues that using a pointing finger to trace geometry worked examples is an example of biologically primary knowledge supporting the construction of biologically secondary knowledge. While tracing instructional materials, more cognitive resources will be generated to support schema construction, leading to better learning outcomes. A series of experiments in the thesis demonstrated that when students were instructed to trace mathematics worked examples during the acquisition phase, they had superior performance and reported lower test difficulty at the test phase than those who were instructed to simply study worked examples without tracing. Furthermore, it was found that the tracing effect was larger when students traced worked examples with their finger touching the paper than without touching the paper. The results suggest that tracing with a pointing finger is a natural and powerful learning strategy, which can support learning by studying worked examples in highly cognitive domains. The findings of the present research may inform instructional designers and school teachers to create learning activities with the incorporation of pointing and tracing movements to improve students' learning.

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Appendix 1: Experimental Materials for Experiment 1

Initial instruction phase

[Instructions for both groups]

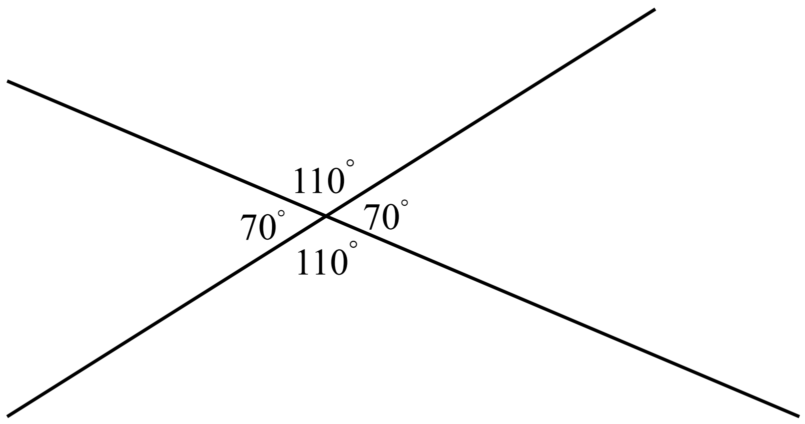
You will now have 5 minutes to study the materials on Angle Relationships on the next 4 pages.

You must read the information carefully and try to understand the information.

If you have read all the pages before the time runs out, please go back to the first page and review the materials you have read.

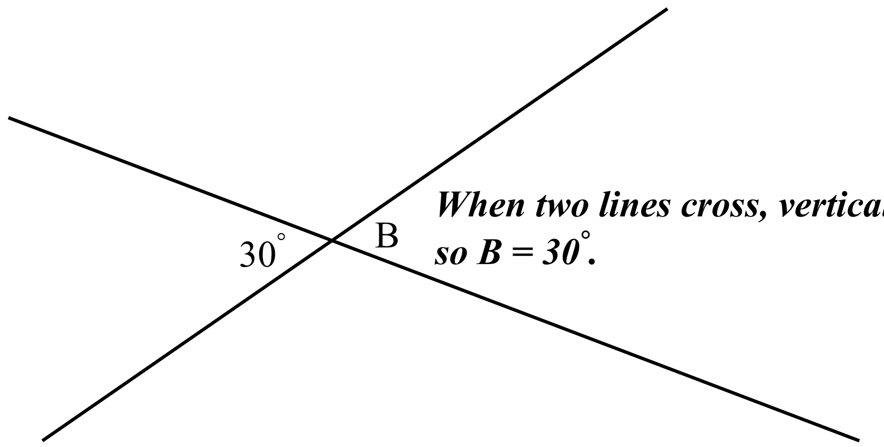
Angle relationship 1:
Vertical Angles

When two lines cross, two pairs of angles opposite each other are formed. The angles in each pair are equal, as in this diagram.



How to use this relationship

Question: What is the value of B?

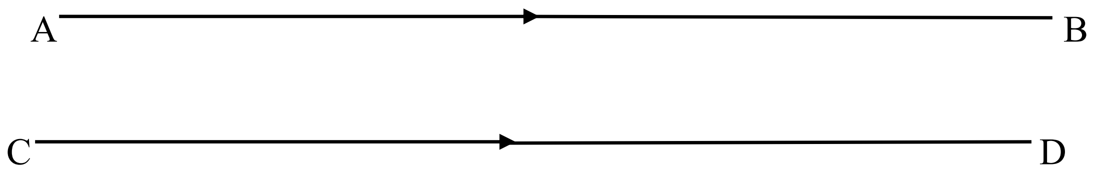


When two lines cross, vertical angles are equal, so B = 30°.

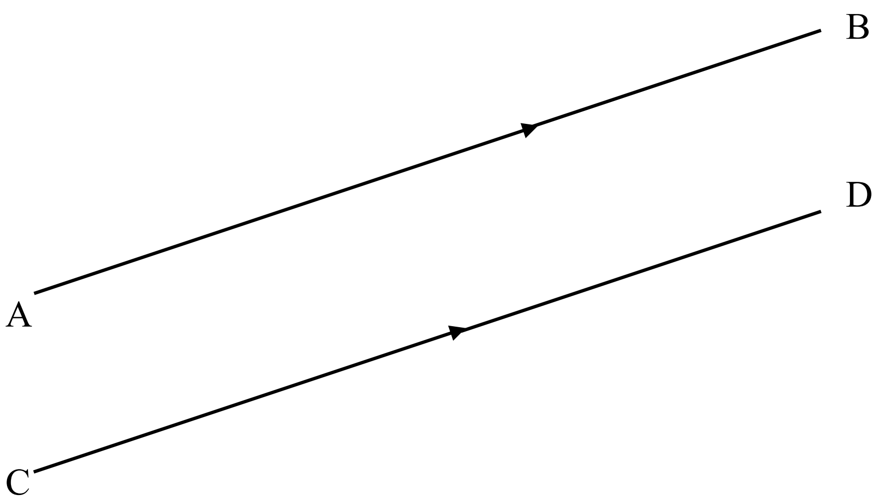
Parallel lines

If two lines point in the same direction and will never cross, the two lines are parallel.

To show the lines are parallel, small arrow marks are noted on the lines, as in these diagrams.



The line AB is parallel to the line CD.

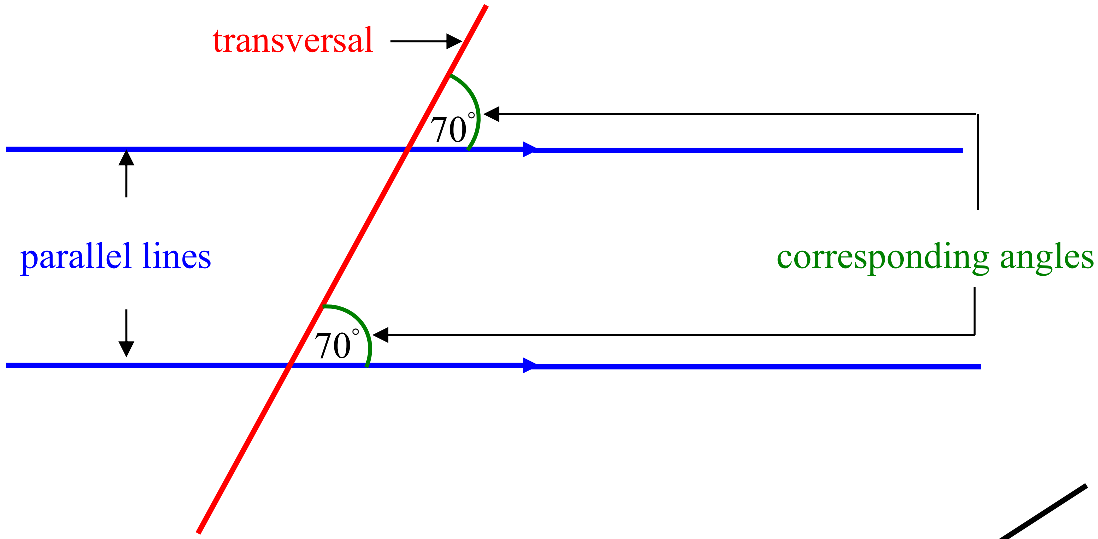


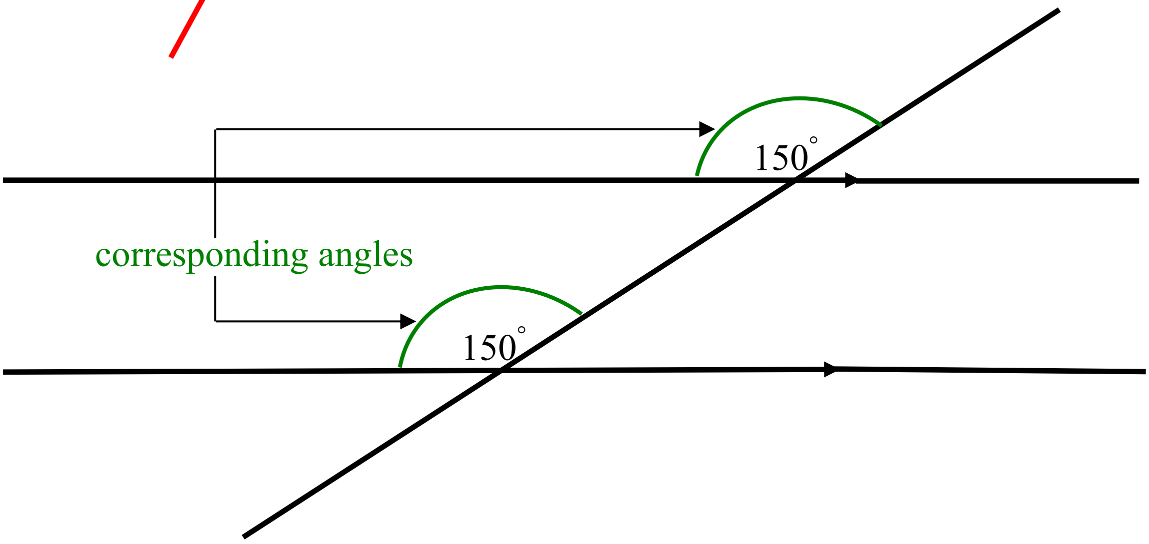
The line AB is parallel to the line CD.

Angle relationship 2:

Corresponding Angles

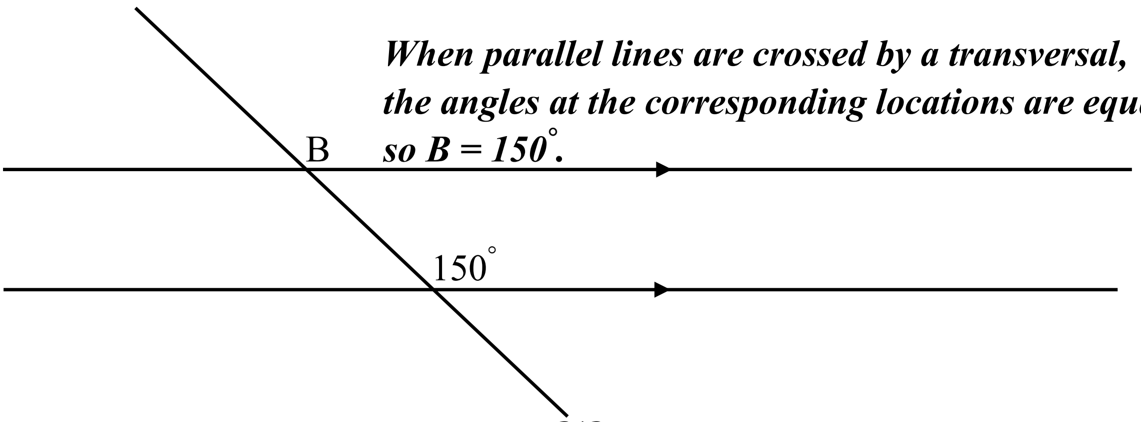
When parallel lines are crossed by another line (called a transversal), the angles at the corresponding locations are equal, as in these diagrams.





How to use this relationship

Question: What is the value of B?

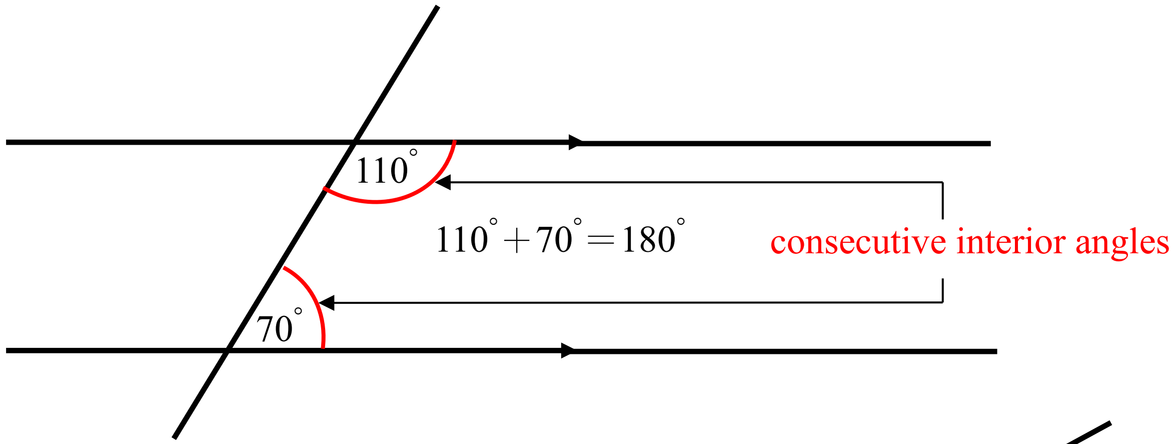


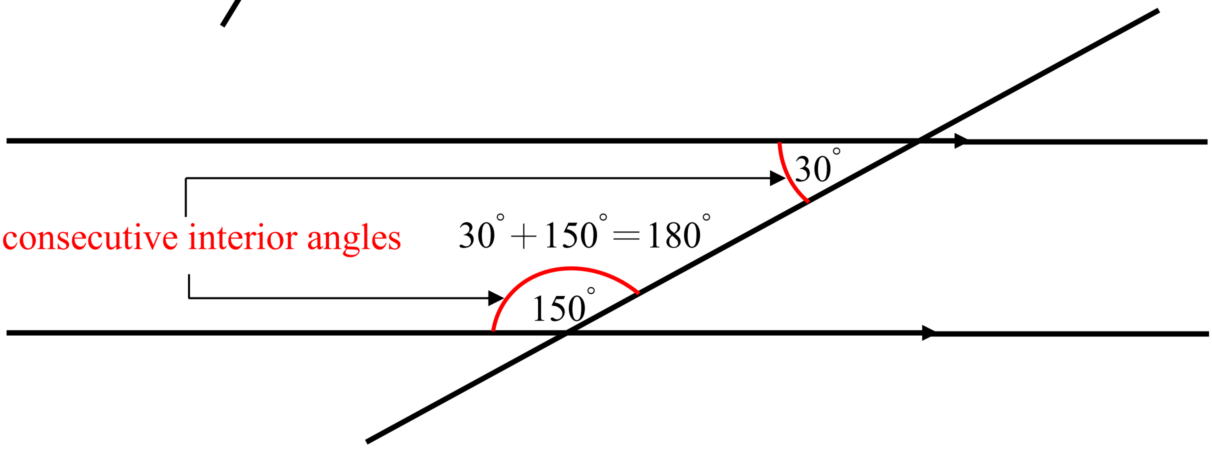
When parallel lines are crossed by a transversal, the angles at the corresponding locations are equal, so B = 150°.

Angle relationship 3:

Consecutive interior angles

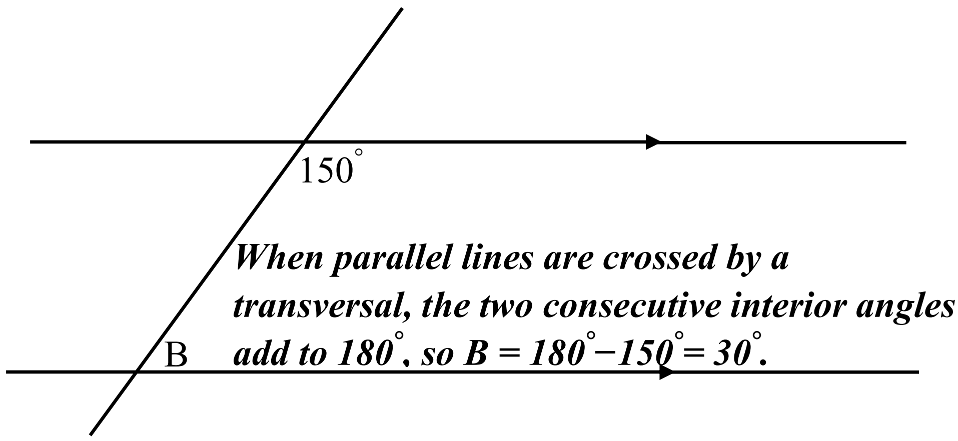
When two parallel lines are crossed by a transversal, the two consecutive interior angles, inside the parallel lines and on the same side of the transversal, are supplementary (add to 180°), as in these diagrams.





How to use this relationship

Question: What is the value of B?



Acquisition phase

[Instructions for the tracing group]

You will now be shown a worked example to study. Please use your index finger of your writing hand to help you learn. You will have 2 minutes to:

(1) Look at the worked example

(2) Read the solution steps in the worked example carefully.

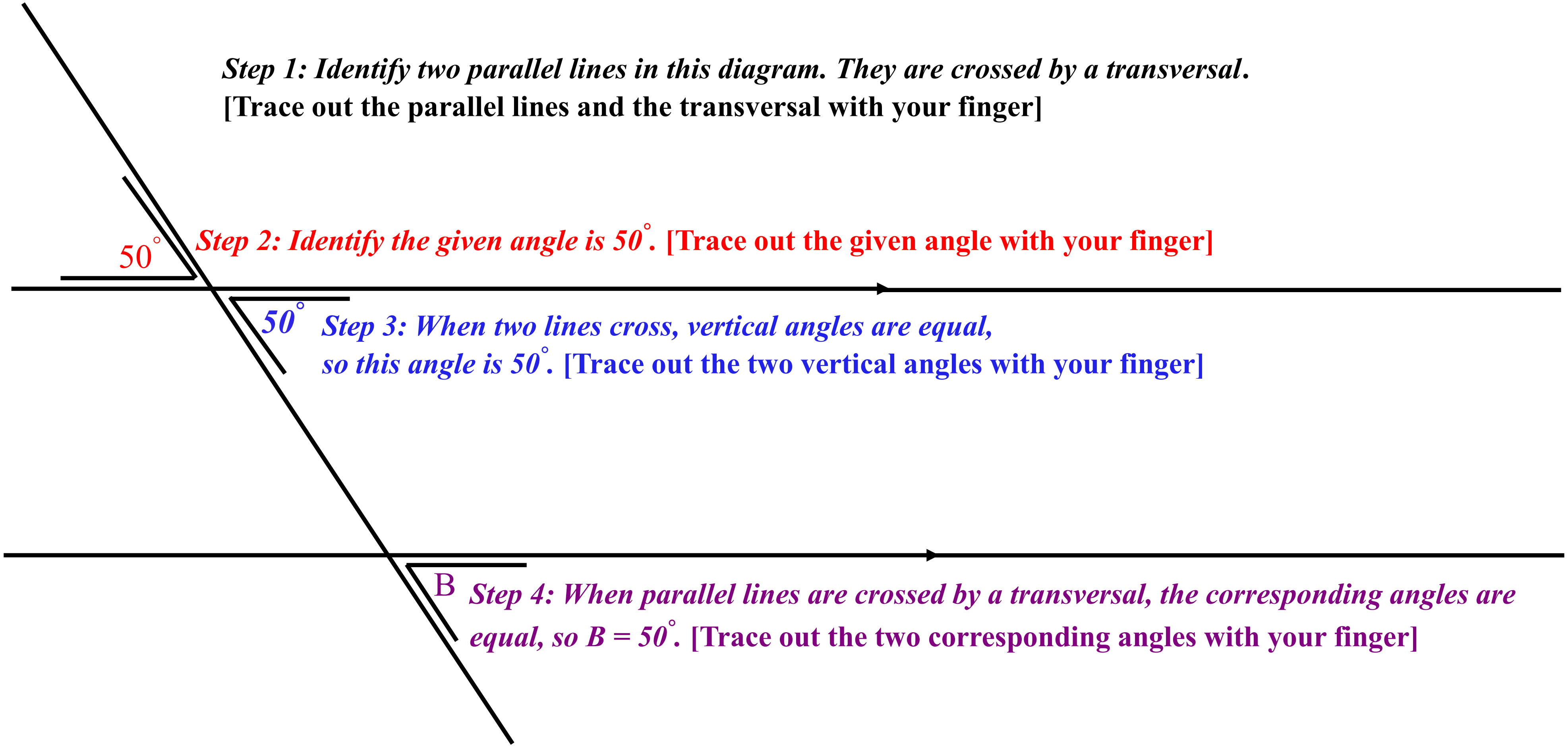
(3) As the instructions in brackets tell you, use your index finger to trace out the diagram on the page.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

Worked example 1:

Question: What is the value of B?

"Given" angles are in normal type; steps of the solution are in ***italic and bold*** type.



Step 1: Identify two parallel lines in this diagram. They are crossed by a transversal. **[Trace out the parallel lines and the transversal with your finger]**

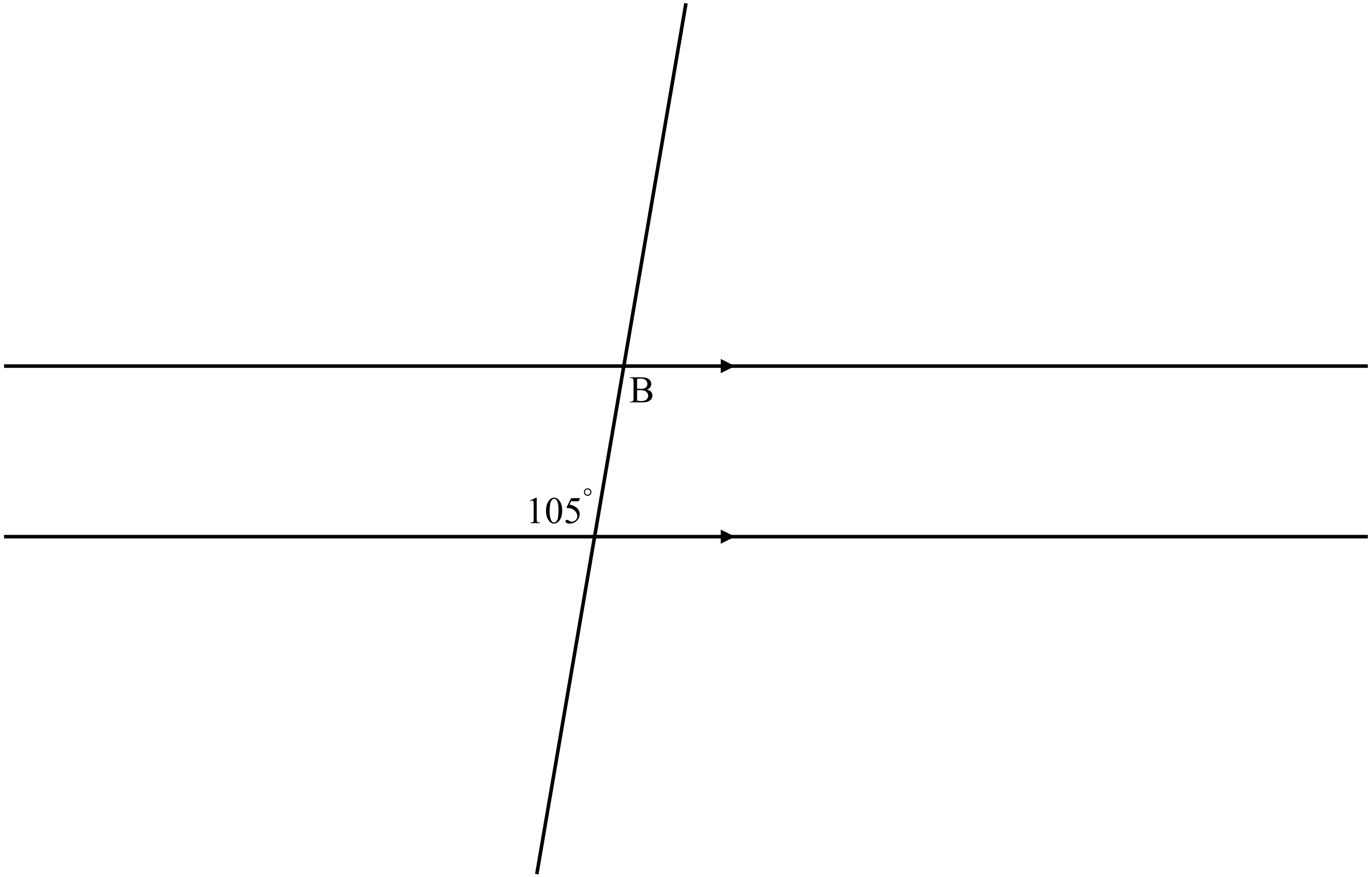
Step 2: Identify the given angle is 50°. **[Trace out the given angle with your finger]**

Step 3: When two lines cross, vertical angles are equal, so this angle is 50°. **[Trace out the two vertical angles with your finger]**

Step 4: When parallel lines are crossed by a transversal, the corresponding angles are equal, so B = 50°. **[Trace out the two corresponding angles with your finger]**

Practice question 1:

Question: What is the value of B?

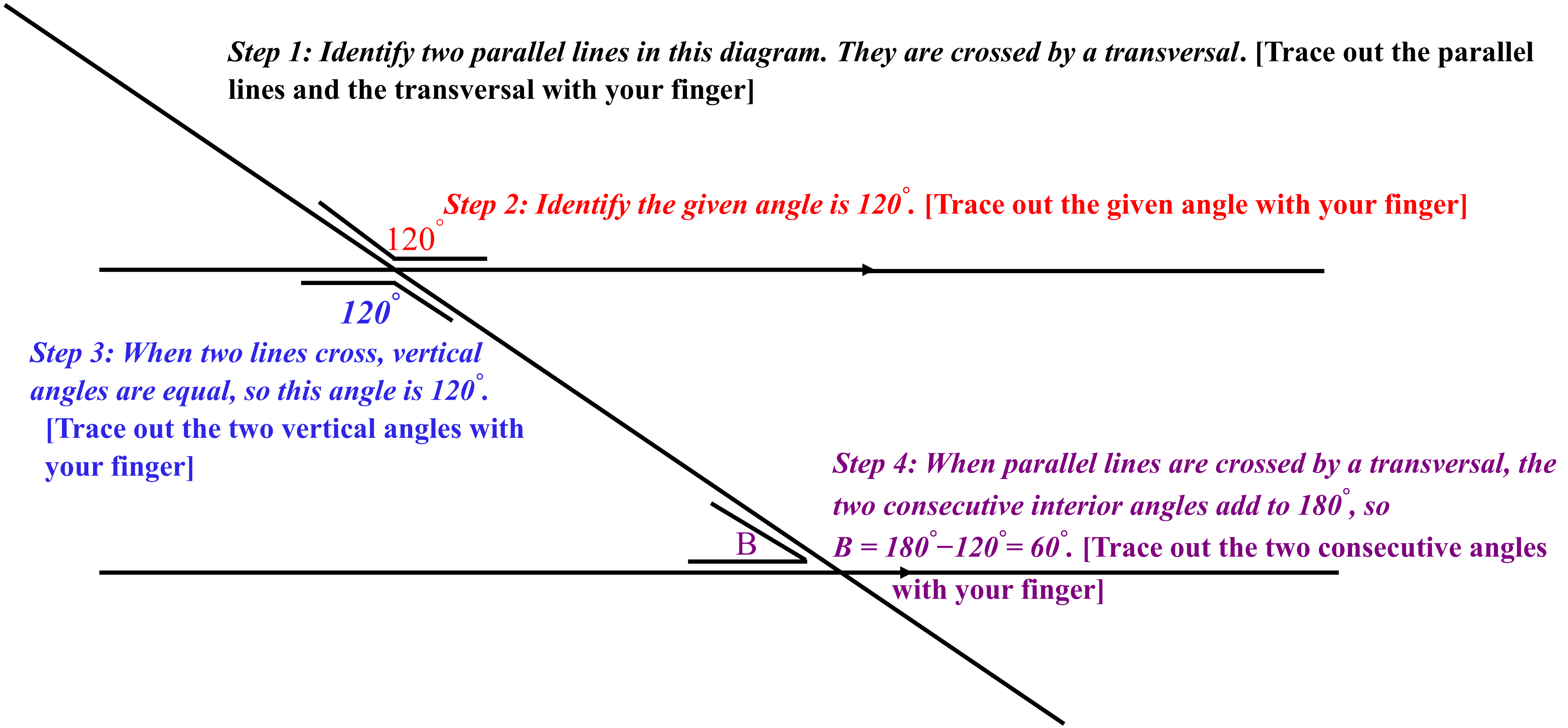


Answer: B = __________

Worked example 2:

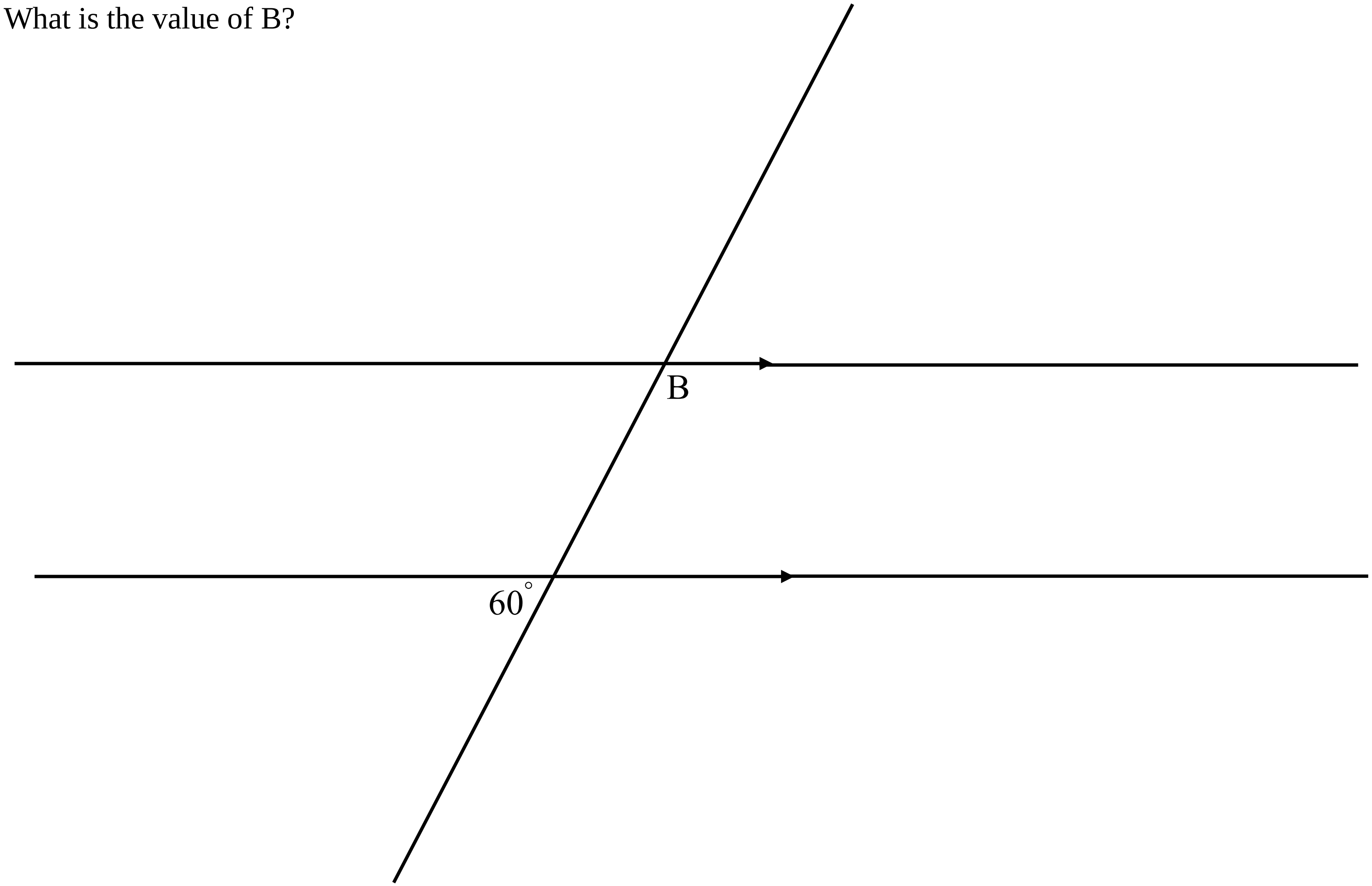
Question: What is the value of B?

"Given" angles are in normal type; steps of the solution are in ***italic and bold*** type.



Practice question 2:

Question: What is the value of B?



Answer: B = __________

Acquisition phase

[Instructions for the non-tracing group]

You will now be shown a worked example to study. Please put your hands on your lap.

You will have 2 minutes to:

(1) Look at the worked example.

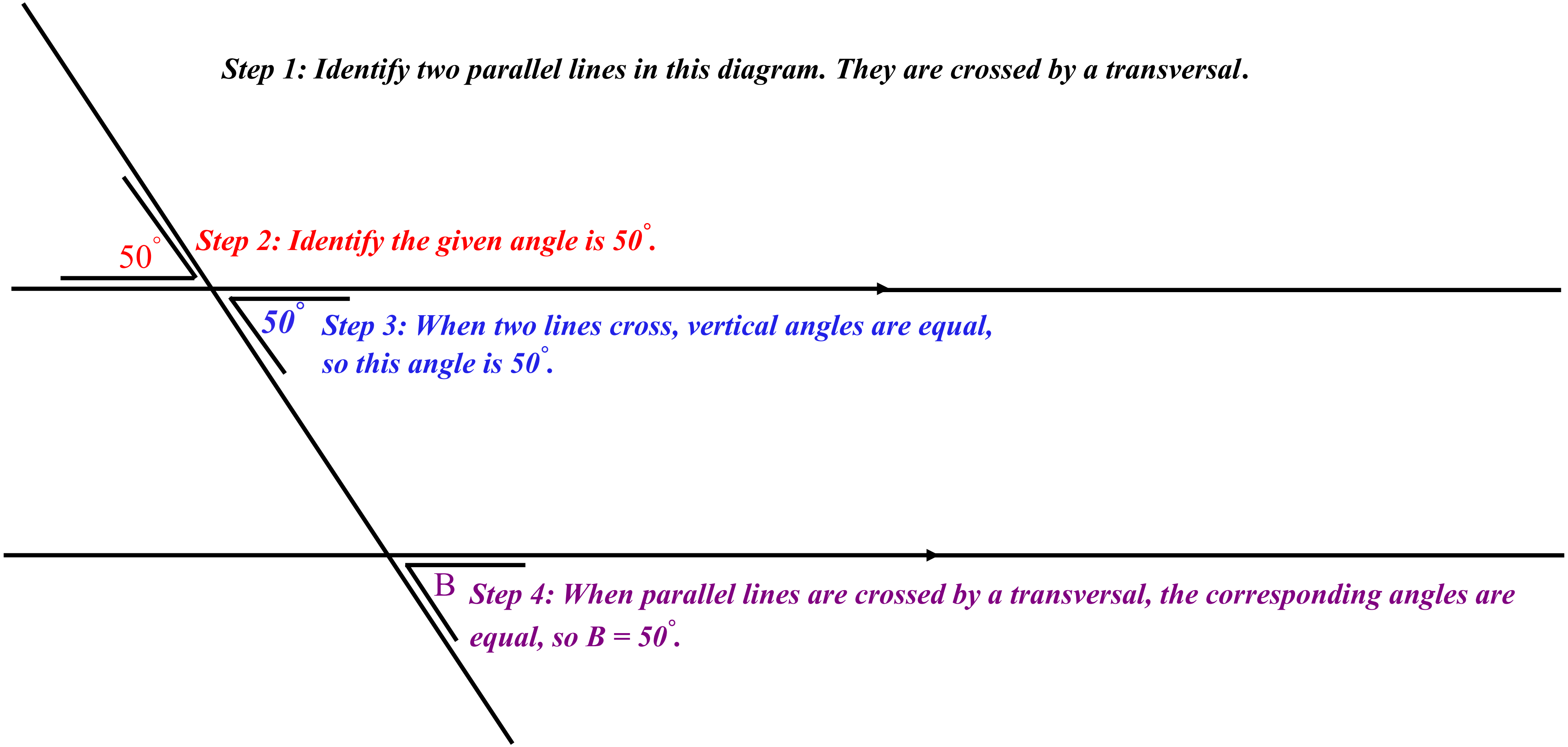
(2) Read the solution steps in the worked example carefully.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

Worked example 1:

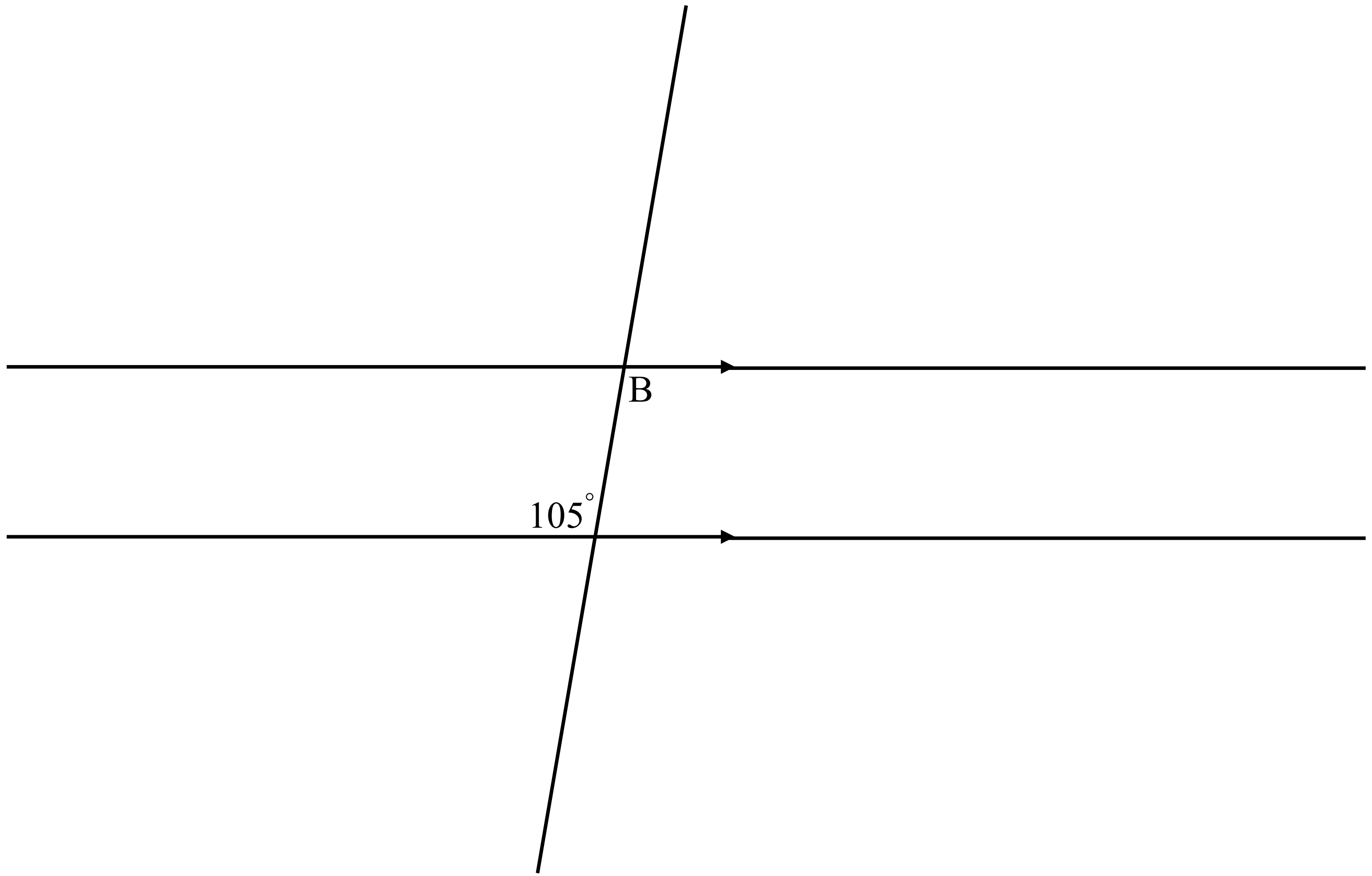
Question: What is the value of B?

"Given" angles are in normal type; steps of the solution are in ***italic and bold*** type.



Practice question 1:

Question: What is the value of B?

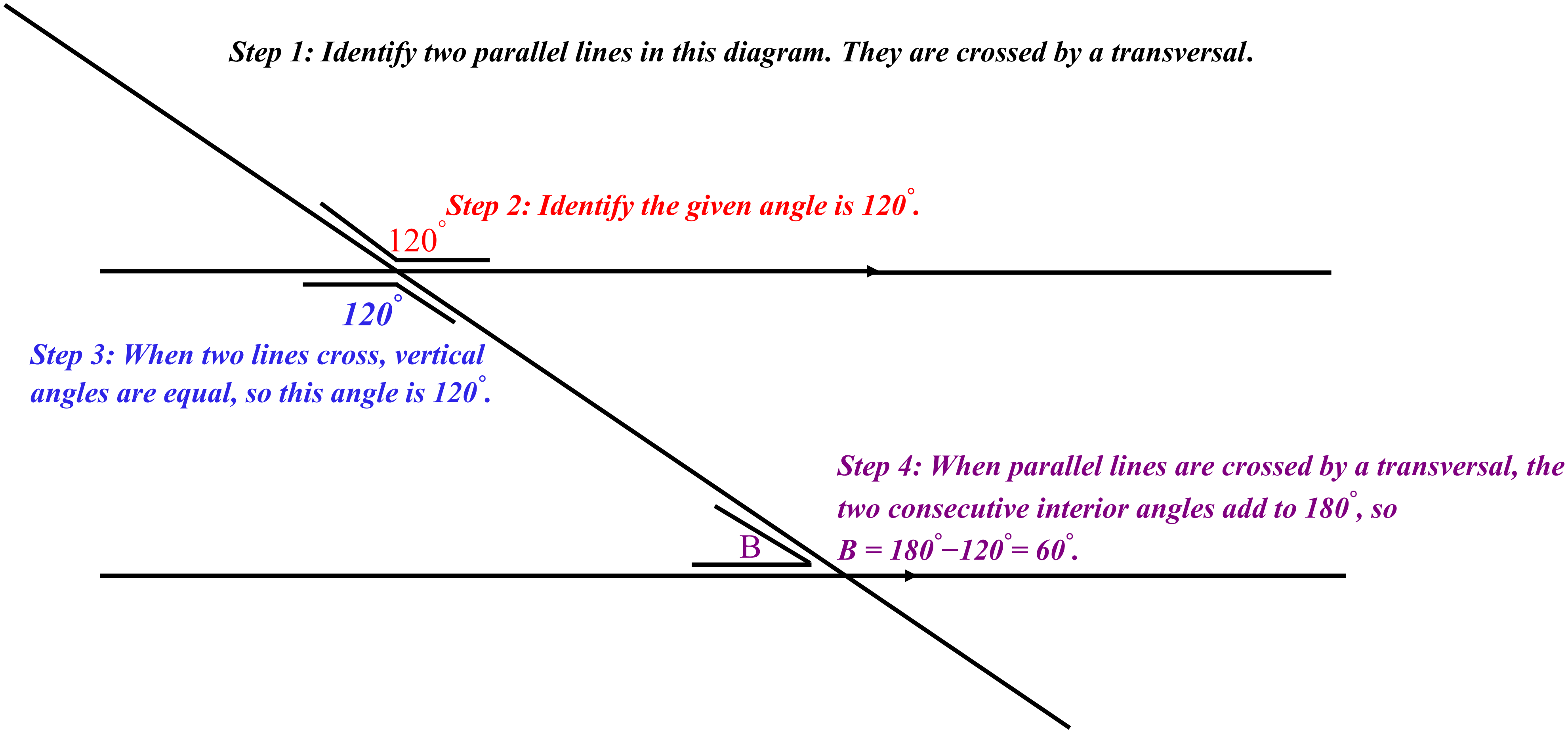


Answer: B = __________

Worked example 2:

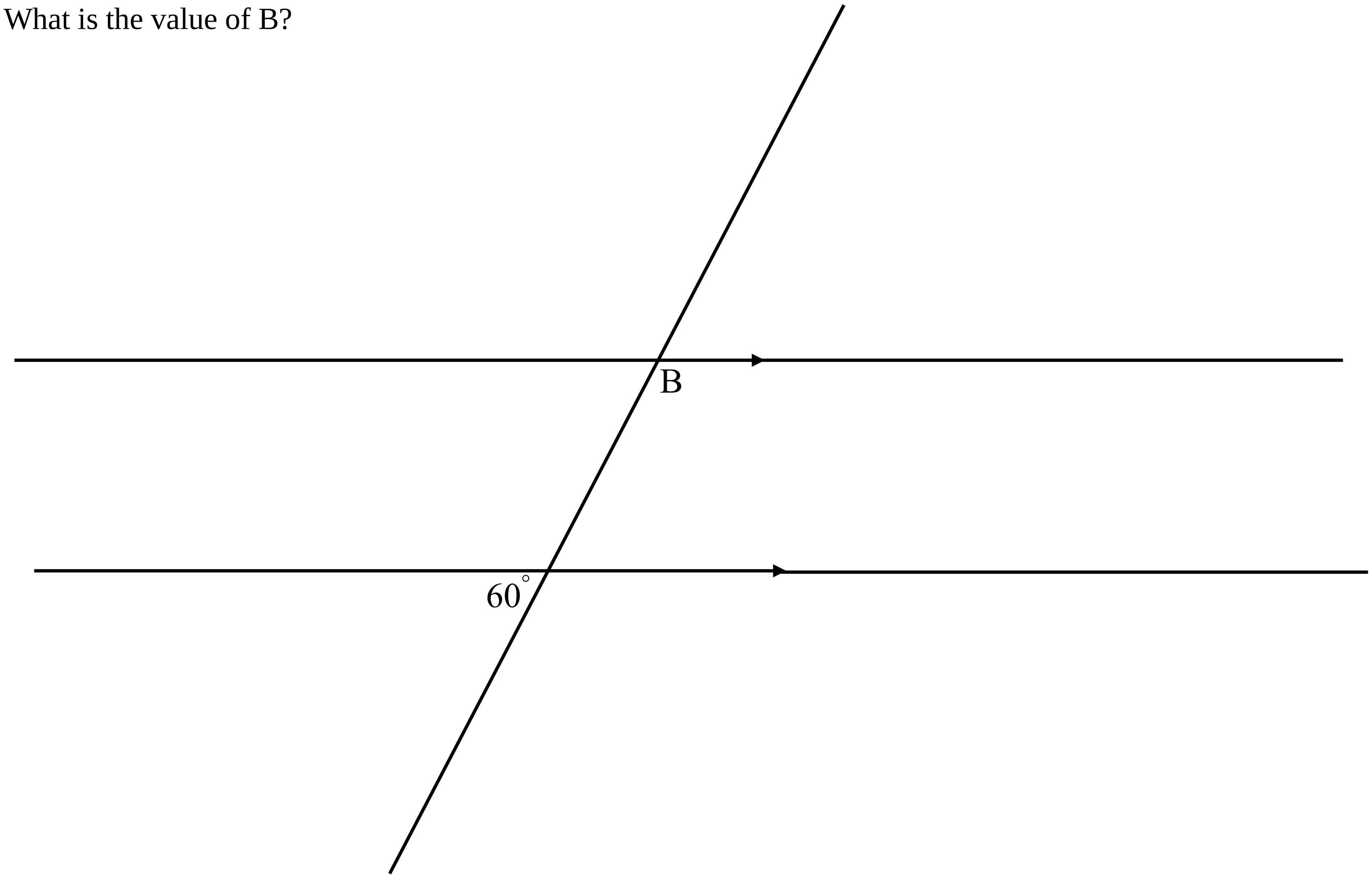
Question: What is the value of B?

"Given" angles are in normal type; steps of the solution are in ***italic and bold*** type.



Practice question 2:

Question: What is the value of B?



Answer: B = __________

Test phase

[Instructions for both groups]

You will now be given 6 problems to solve.

Please apply the angle relationships you have just learned to solve the problems and write down the working for each step to your solution on the diagrams.

You will have up to 2 minutes to solve each problem.

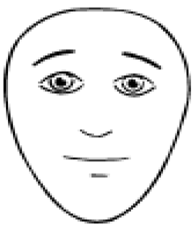
If you work out an incorrect answer, I will tell you and then you can continue trying to work out an answer.

If you have any questions about the test, please ask now.

Cognitive Load Ratings (to be collected after each of the questions below)

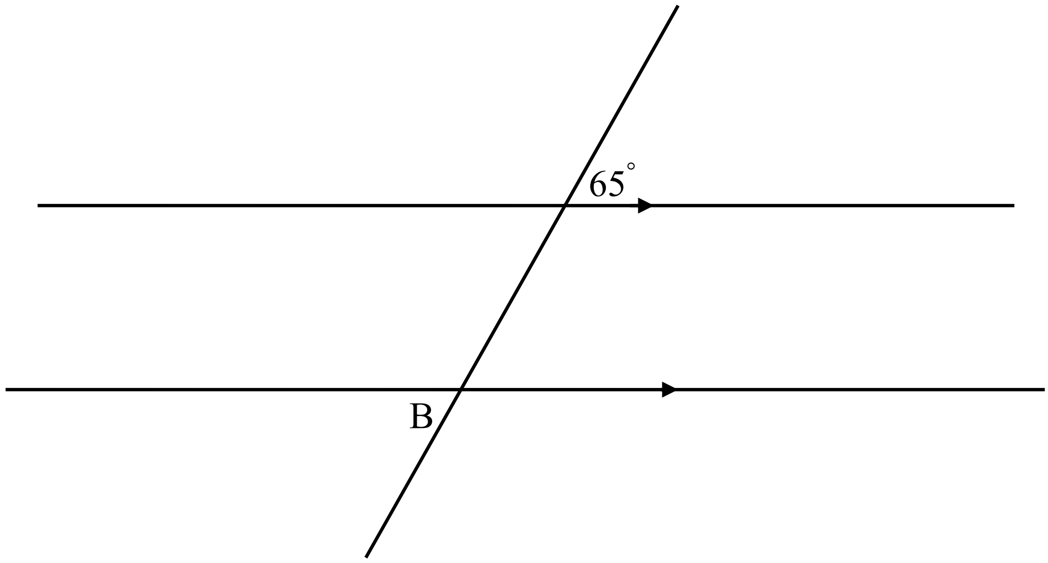
[Instructions for both groups]

The faces show how people feel when trying to solve a problem. The left-most face shows people find it very easy to solve a problem. The right-most face shows people find it very difficult to solve a problem. After solving each problem, you will be asked how you felt about solving this problem. Please point out if you found the problem very easy, very difficult, or somewhere in the middle.

 Very easy 1	2	3	4	 Very difficult 5

Question 1

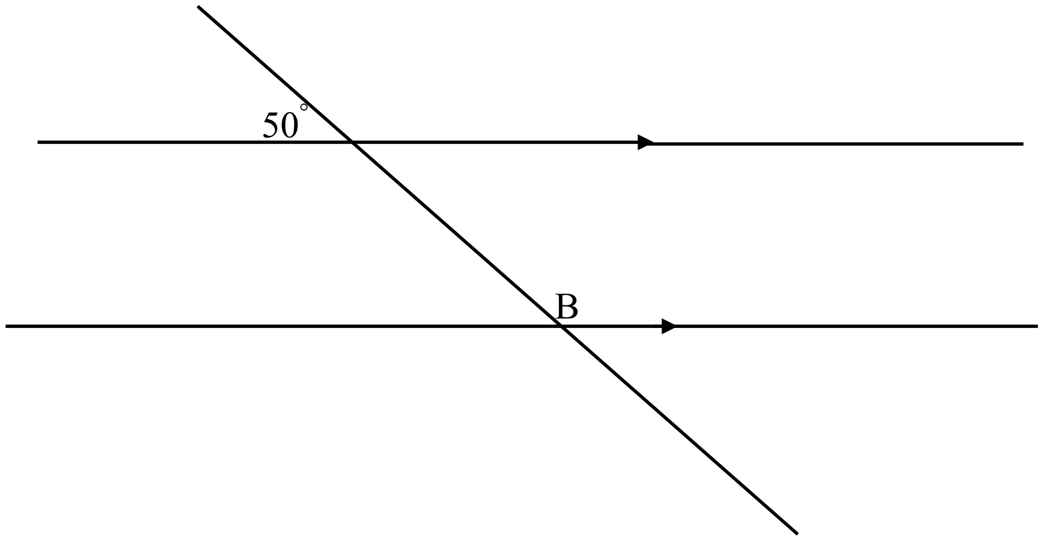
Question: What is the value of B?



Answer: B = _________

Question 2

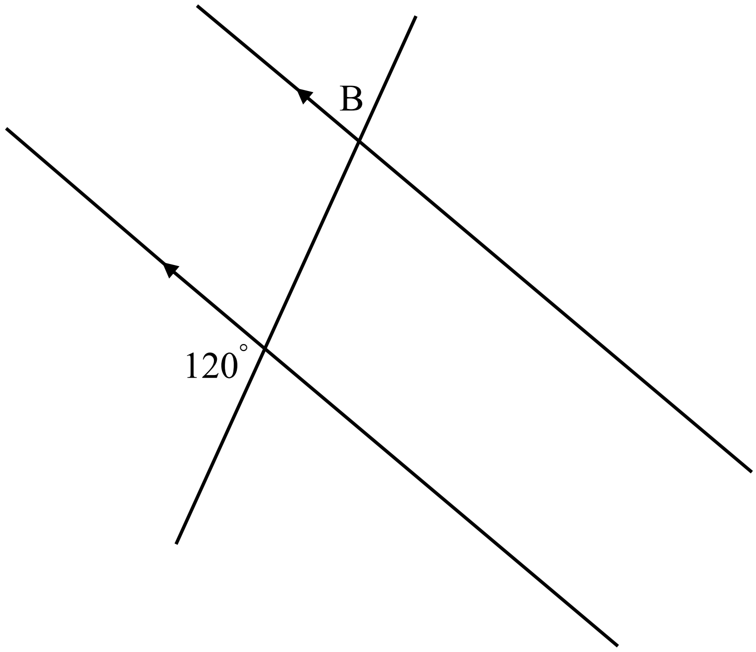
Question: What is the value of B?



Answer: B = _________

Question 3

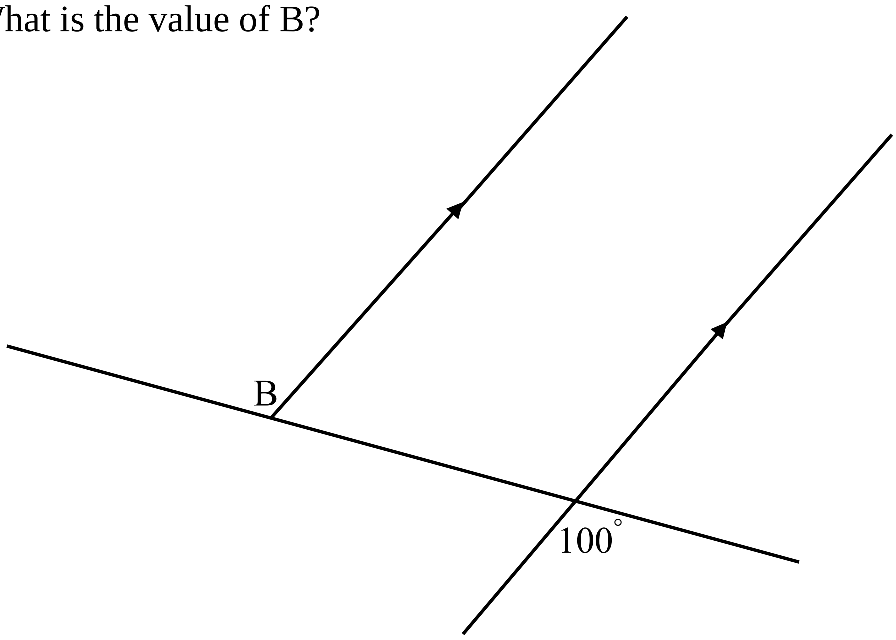
Question: What is the value of B?



Answer: B = _________

Question 4

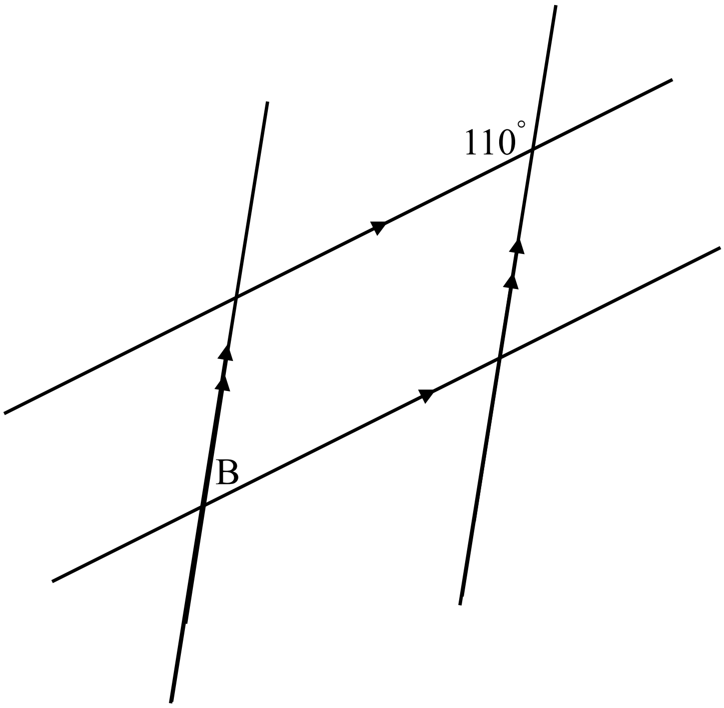
Question: What is the value of B?



Answer: B = _________

Question 5

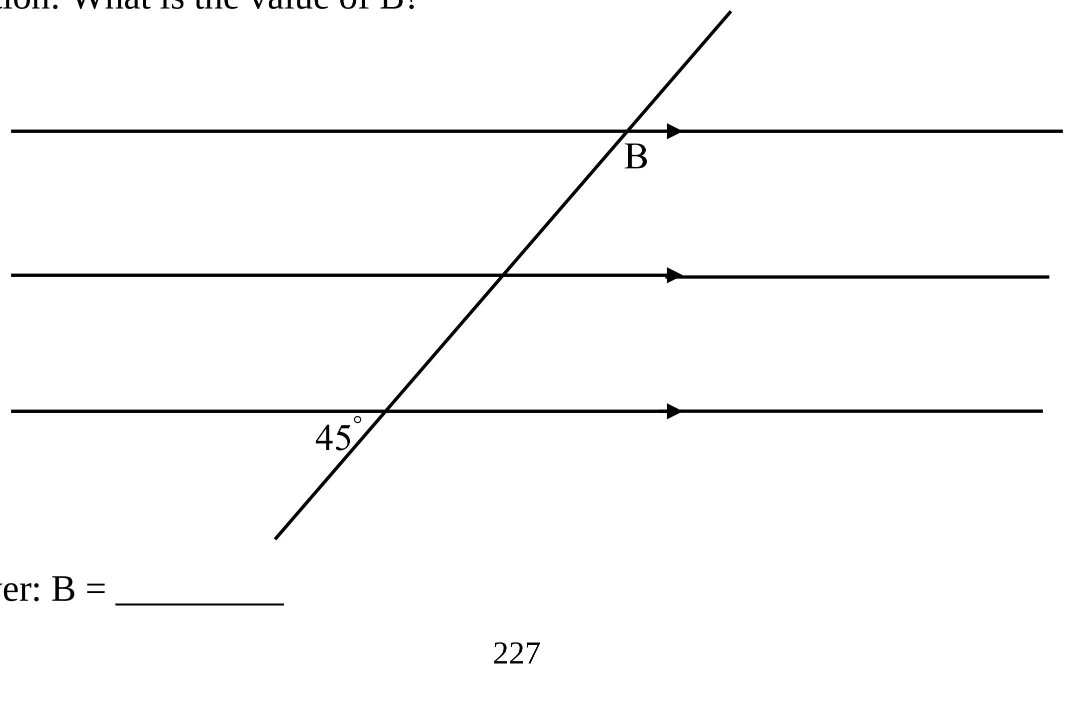
Question: What is the value of B?



Answer: B = _________

Question 6

Question: What is the value of B?



Answer: B = _________

Appendix 2: Experimental Materials for Experiment 2

Initial instruction phase

[Instructions for both groups]

You will now have 5 minutes to study the materials on Angle Relationships on the next 5 pages.

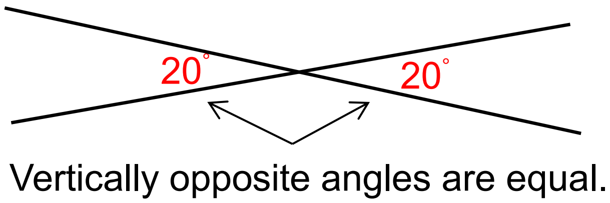
You must read the information carefully and try to understand the information.

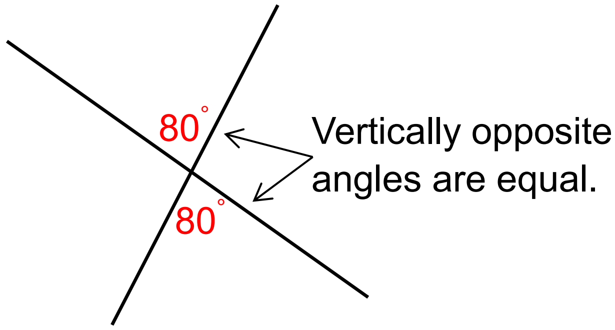
If you have read all the pages before the time runs out, please go back to the first page and review the materials you have read.

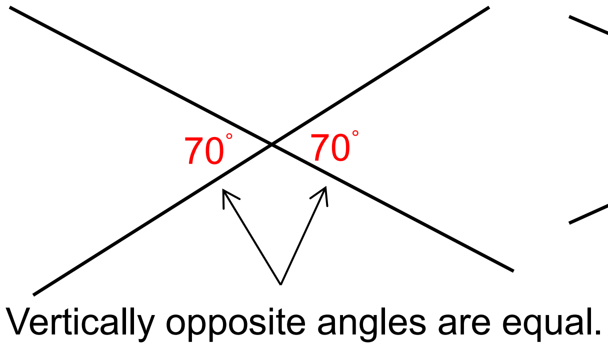
Angle relationship 1:

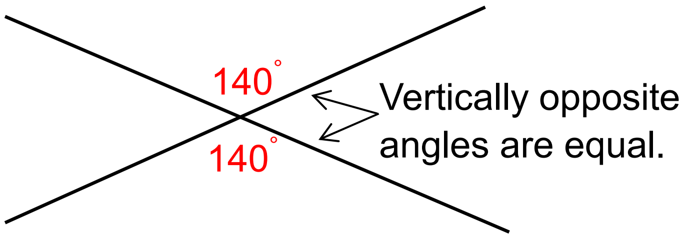
Vertically opposite angles

When two lines cross, the angles vertically opposite each other are equal.



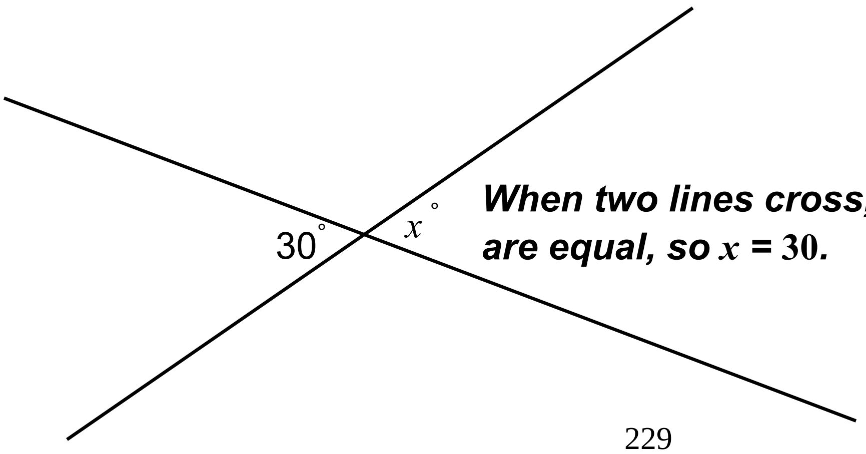






How to use this relationship

Question: What is the value of x?

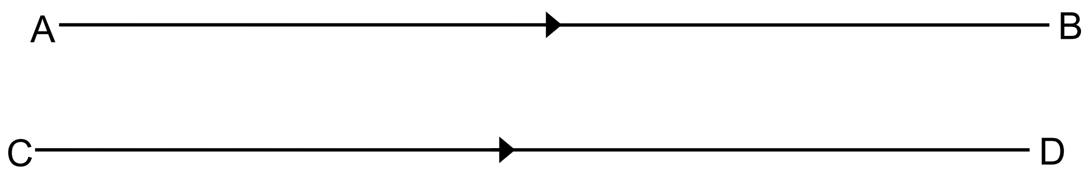


When two lines cross, vertically opposite angles are equal, so $x = 30$.

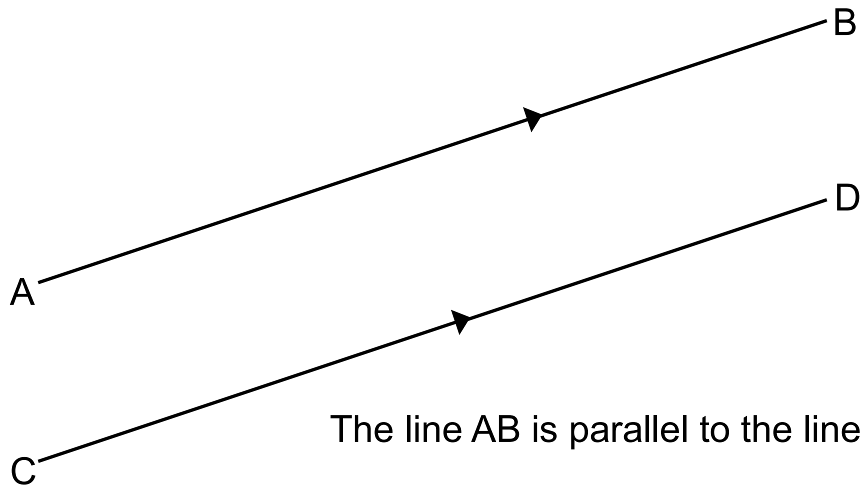
Parallel lines

If two lines point in the same direction and will never cross, the two lines are parallel.

To show the lines are parallel, small arrow marks are noted on the lines, as in these diagrams.

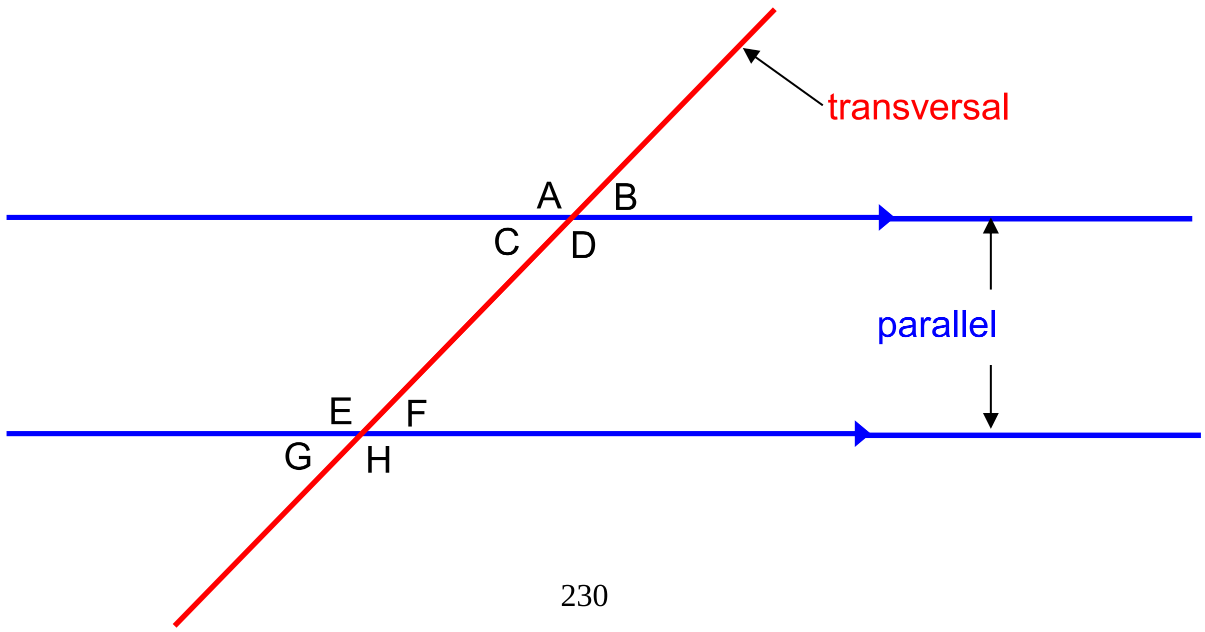


The line AB is parallel to the line CD.



The line AB is parallel to the line CD.

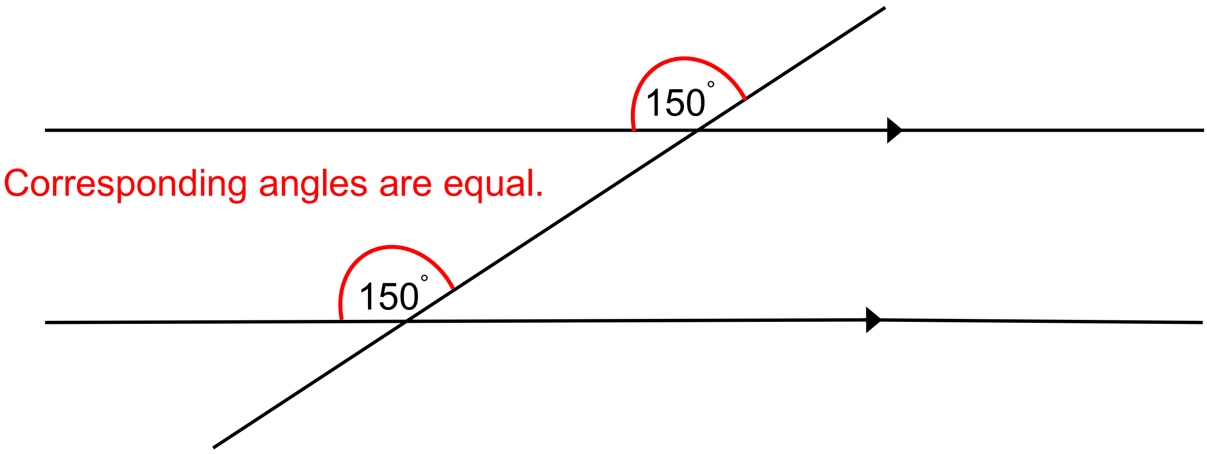
When parallel lines are crossed by another line (which is called a transversal), several angles (for example, A, B, C, D, E, F, G, H) are formed.

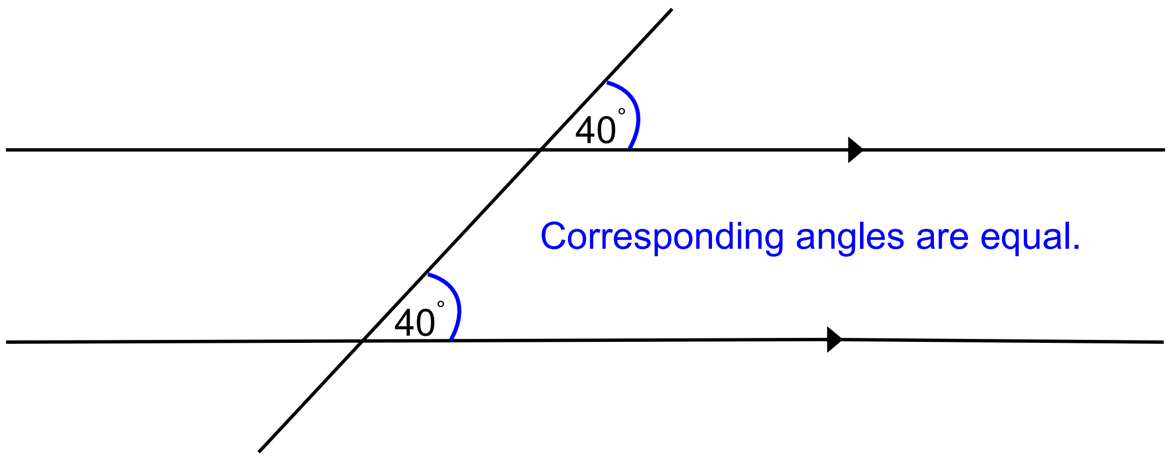


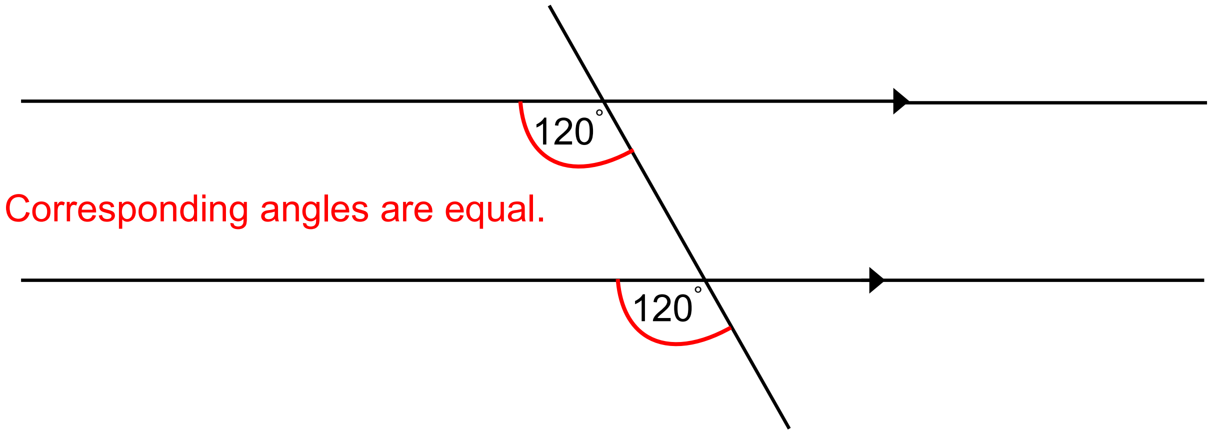
Angle relationship 2:

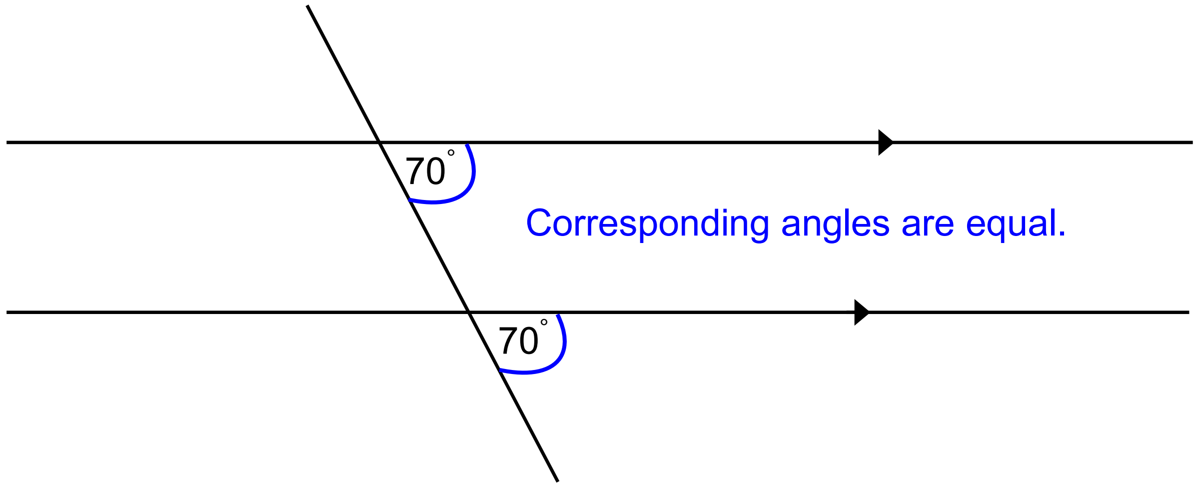
Corresponding angles

When parallel lines are crossed by a transversal, the angles at matching locations are equal.



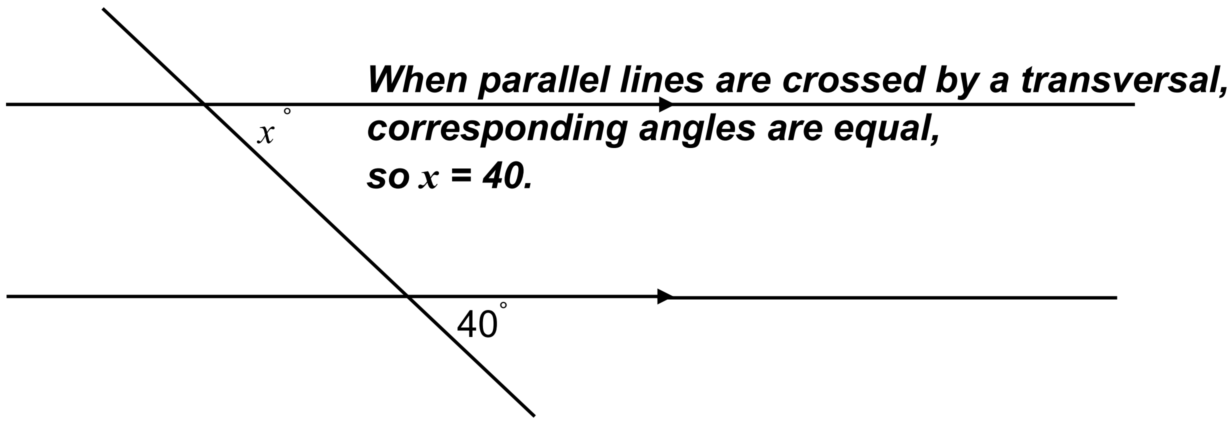






How to use this relationship

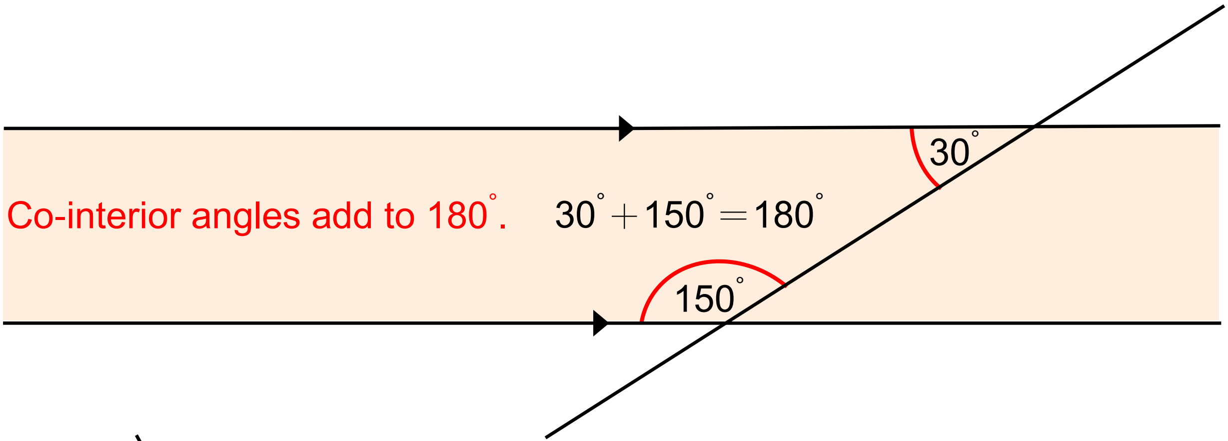
Question: What is the value of x?

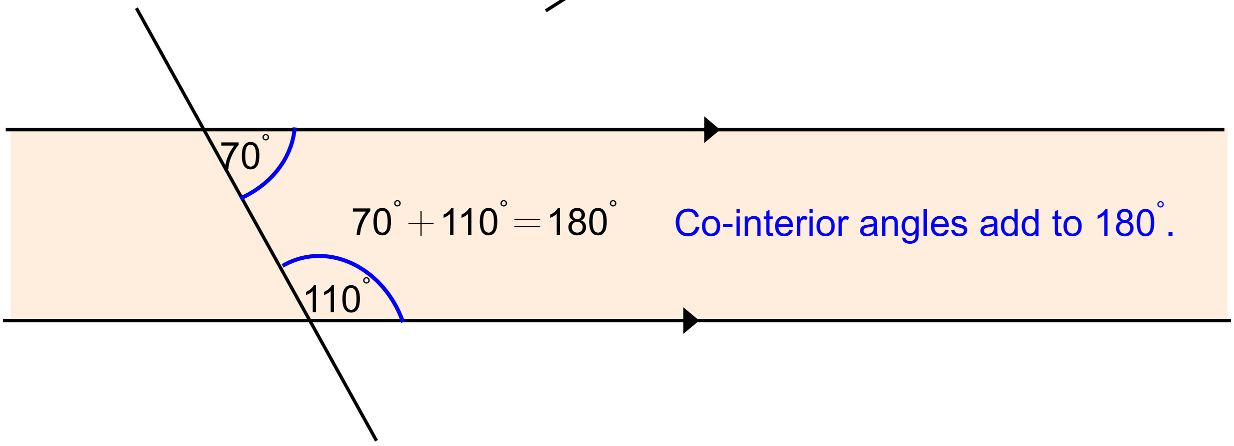


Angle relationship 3:

Co-interior angles

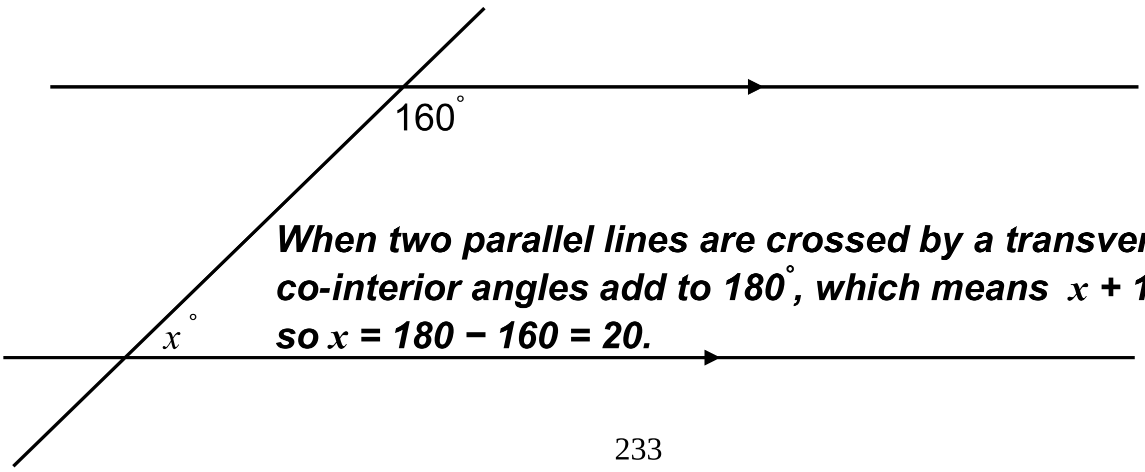
When two parallel lines are crossed by a transversal, the two angles <u>which are between the parallel lines and on the same side of the transversal</u> add to 180°.





How to use this relationship

Question: What is the value of x?



When two parallel lines are crossed by a transversal, co-interior angles add to 180°, which means $x + 160 = 180$, so $x = 180 - 160 = 20$.

Acquisition phase

[Instructions for the tracing group]

You will now be shown a worked example to study. Please use your index finger of your writing hand to help you learn. You will have 2 minutes to:

(1) Look at the worked example

(2) Read the solution steps in the worked example carefully.

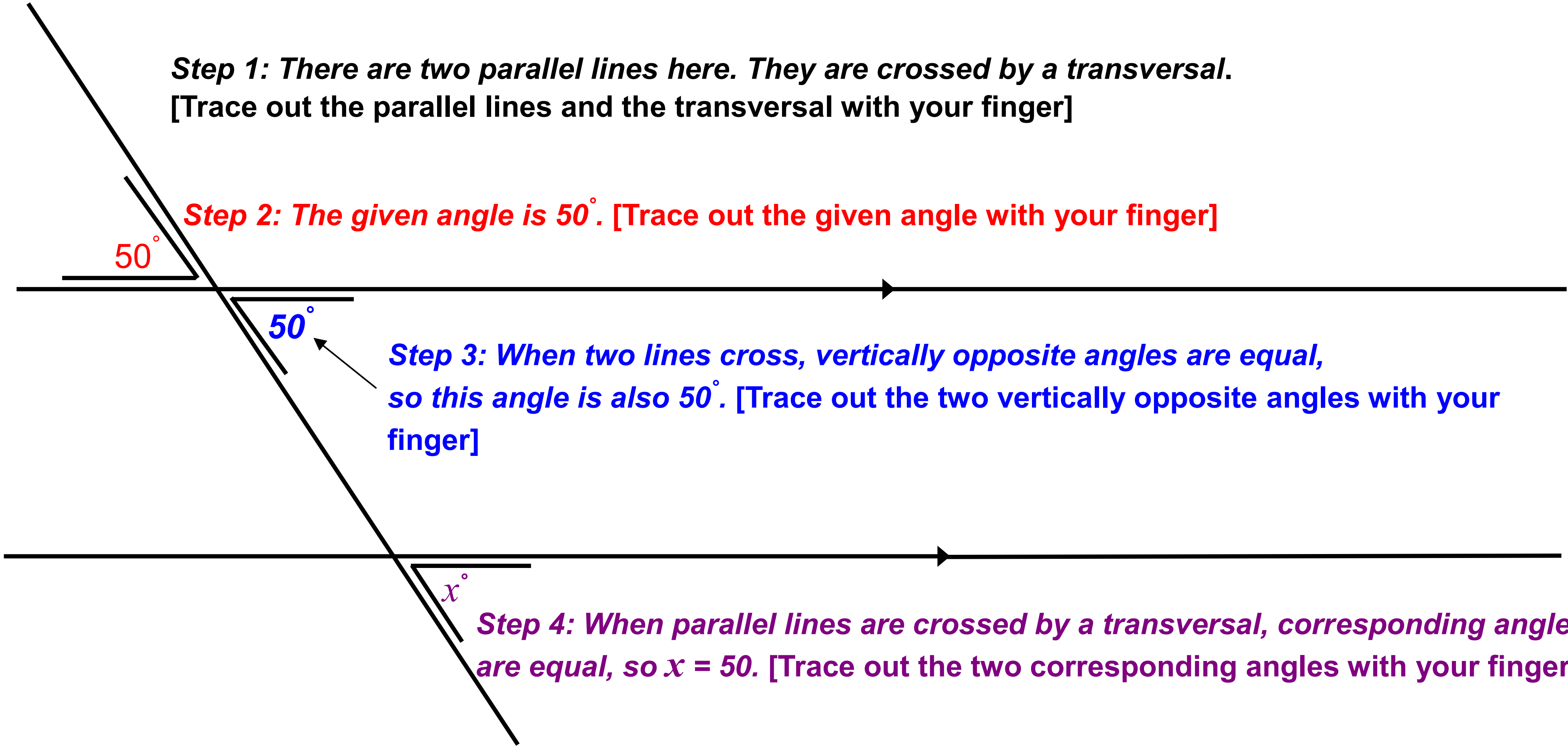
(3) As the instructions in brackets tell you, use your index finger to trace out the diagram on the page.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

"Given" angles are in normal type; steps of the solution are in ***italic and bold*** type.

Worked example 1:

Question: What is the value of x?



***Step 1: There are two parallel lines here. They are crossed by a transversal*.**
[Trace out the parallel lines and the transversal with your finger]

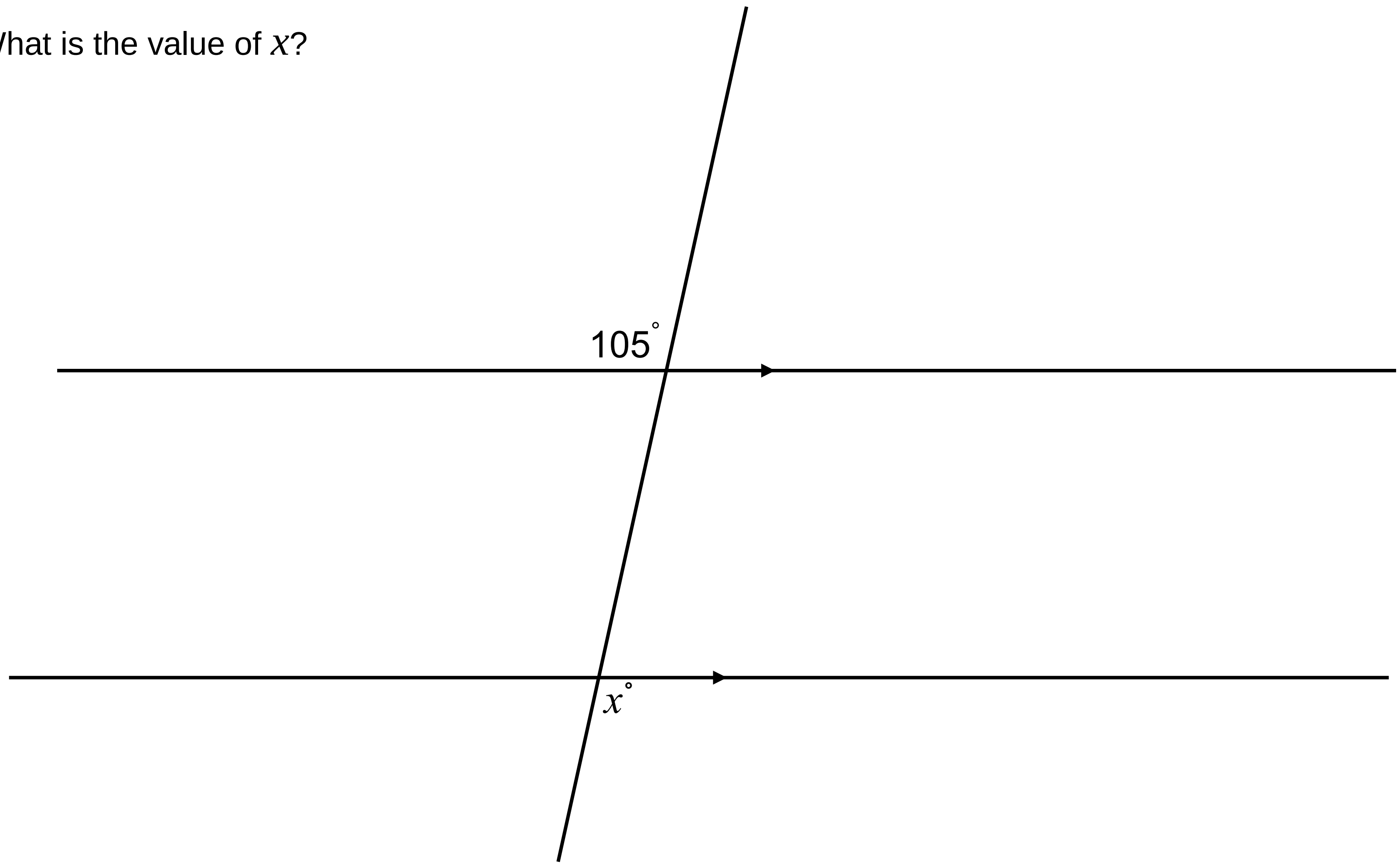
***Step 2: The given angle is 50°.* [Trace out the given angle with your finger]**

***Step 3: When two lines cross, vertically opposite angles are equal, so this angle is also 50°.* [Trace out the two vertically opposite angles with your finger]**

***Step 4: When parallel lines are crossed by a transversal, corresponding angles are equal, so x = 50.* [Trace out the two corresponding angles with your finger]**

Practice question 1:

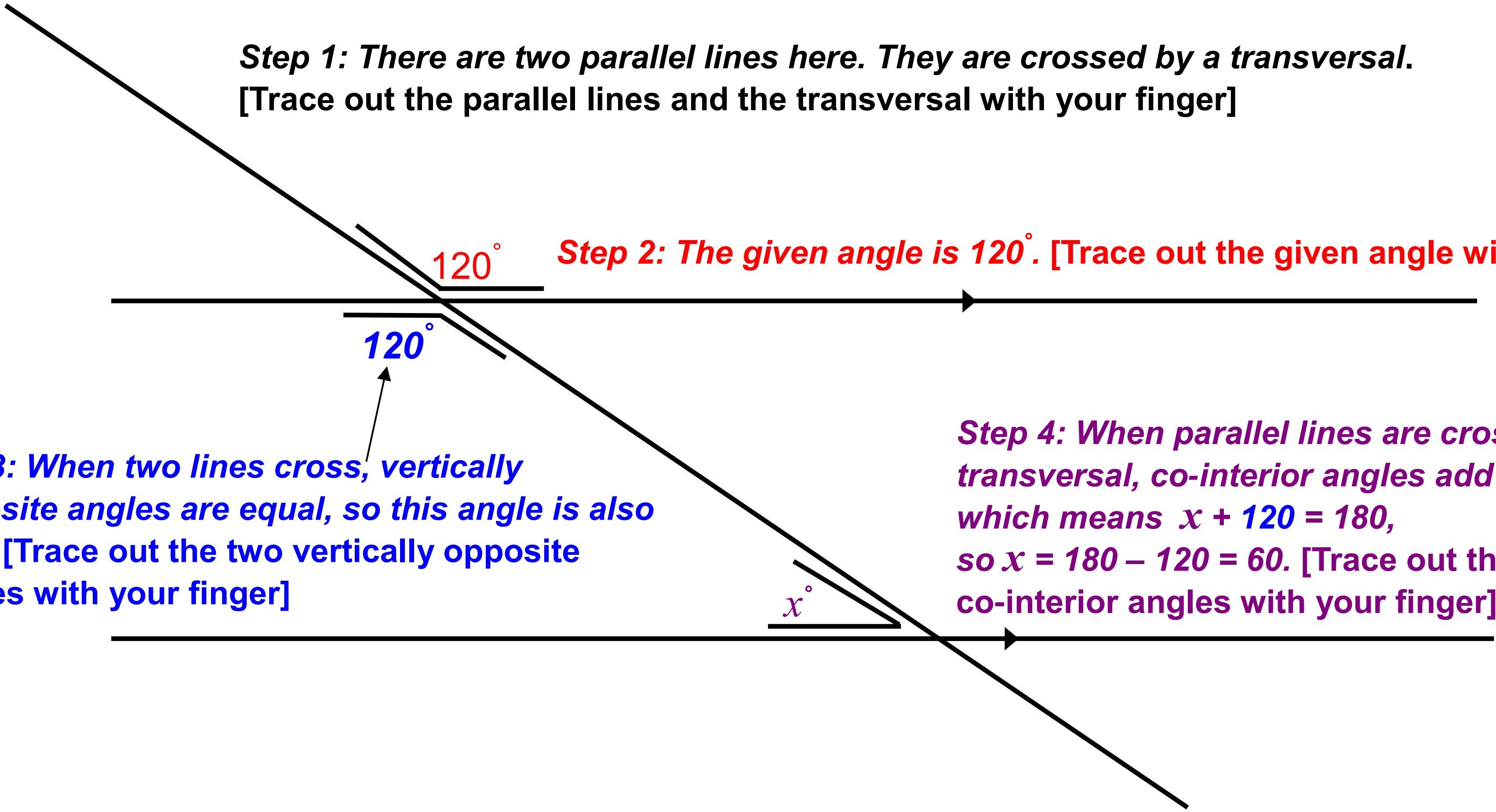
Question: What is the value of x?



Answer: x = __________

Worked example 2:

Question: What is the value of x?



***Step 1: There are two parallel lines here. They are crossed by a transversal*.**
[Trace out the parallel lines and the transversal with your finger]

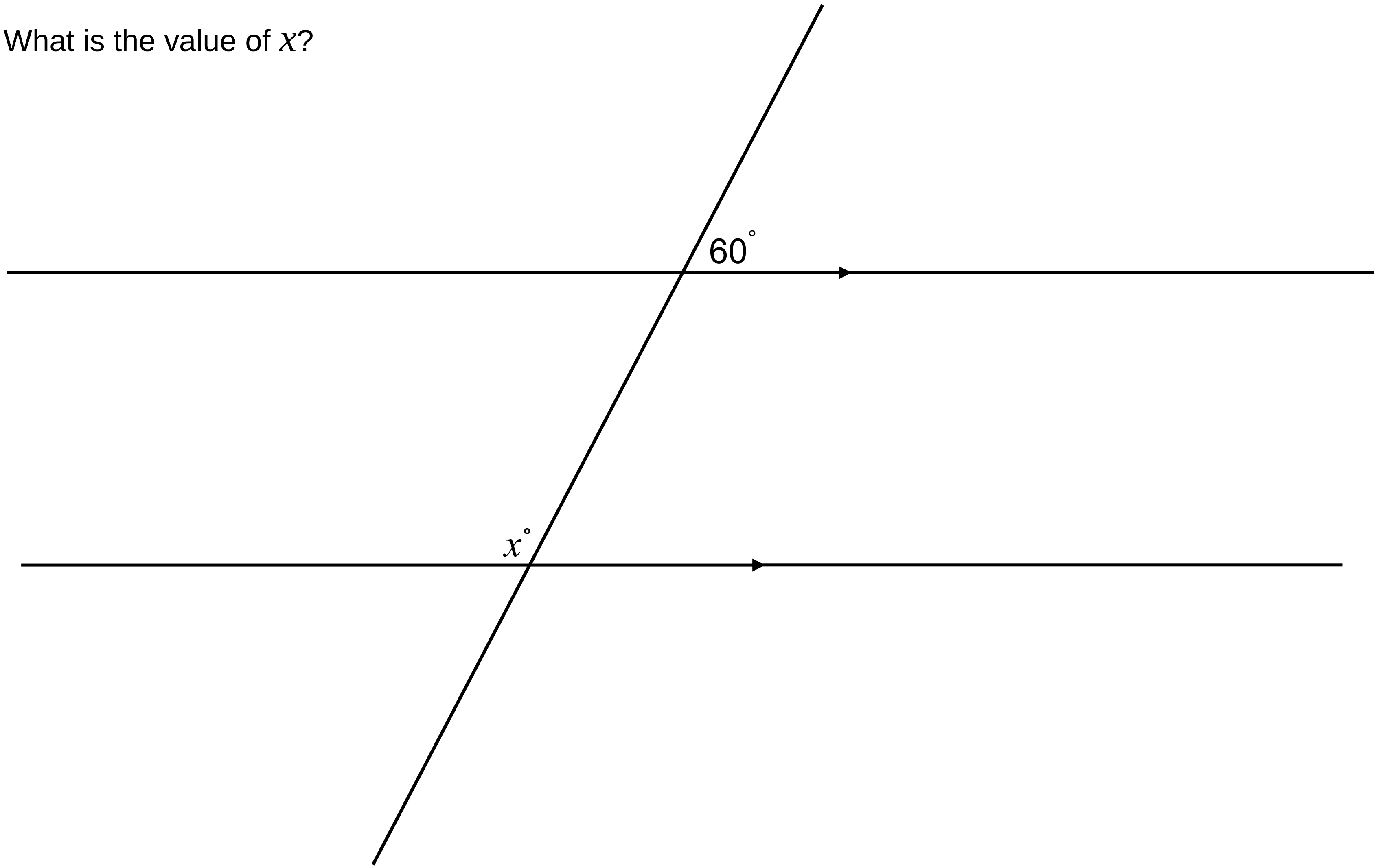
***Step 2: The given angle is 120°.* [Trace out the given angle with your finger]**

***Step 3: When two lines cross, vertically opposite angles are equal, so this angle is also 120°.* [Trace out the two vertically opposite angles with your finger]**

***Step 4: When parallel lines are crossed by a transversal, co-interior angles add to 180°, which means $x + 120 = 180$, so $x = 180 - 120 = 60$.* [Trace out the two co-interior angles with your finger]**

Practice question 2:

Question: What is the value of x?



Answer: x = __________

Acquisition phase

[Instructions for the non-tracing group]

You will now be shown a worked example to study. Please use your index finger of your writing hand to help you learn. You will have 2 minutes to:

(1) Look at the worked example

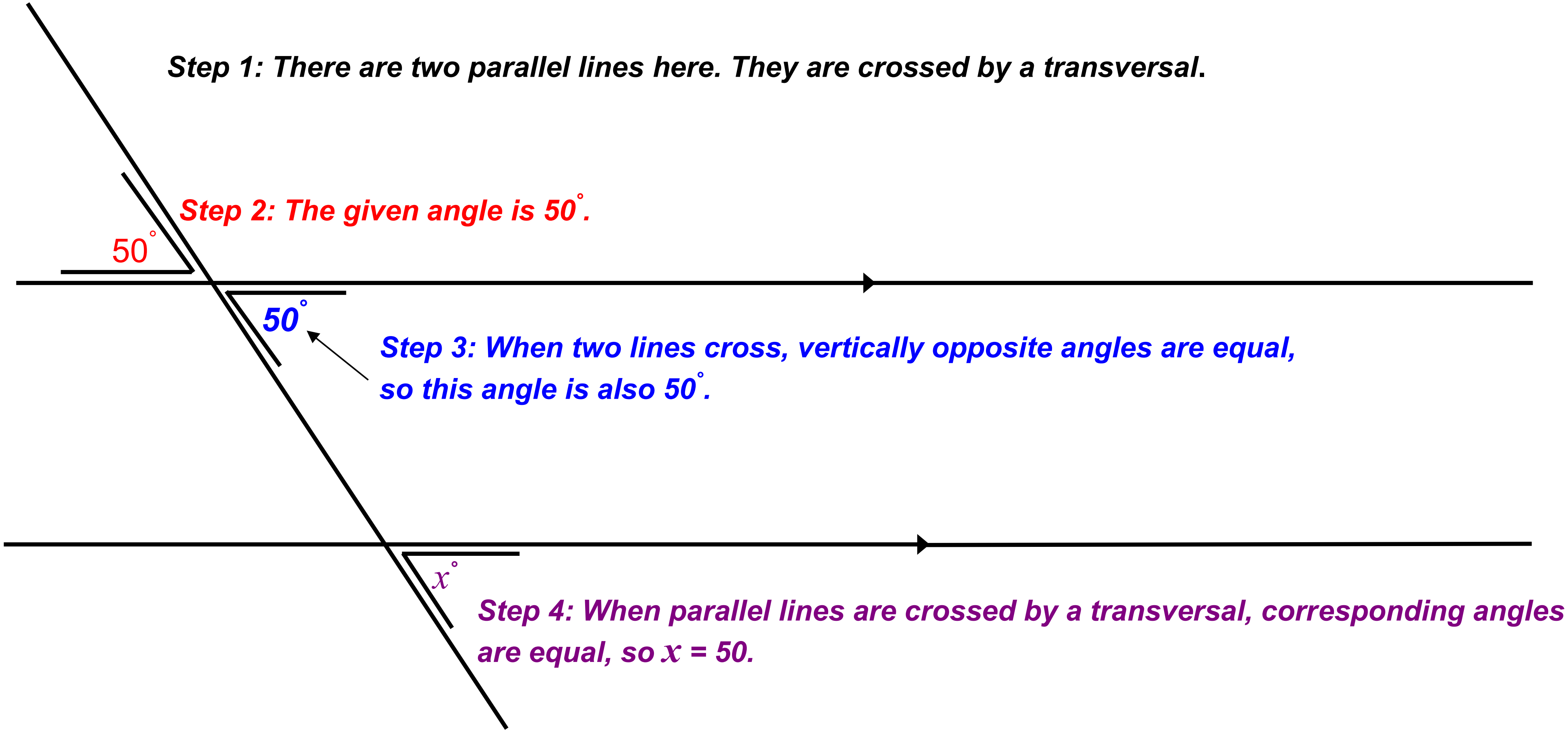
(2) Read the solution steps in the worked example carefully.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

“Given” angles are in normal type; steps of the solution are in ***italic and bold*** type.

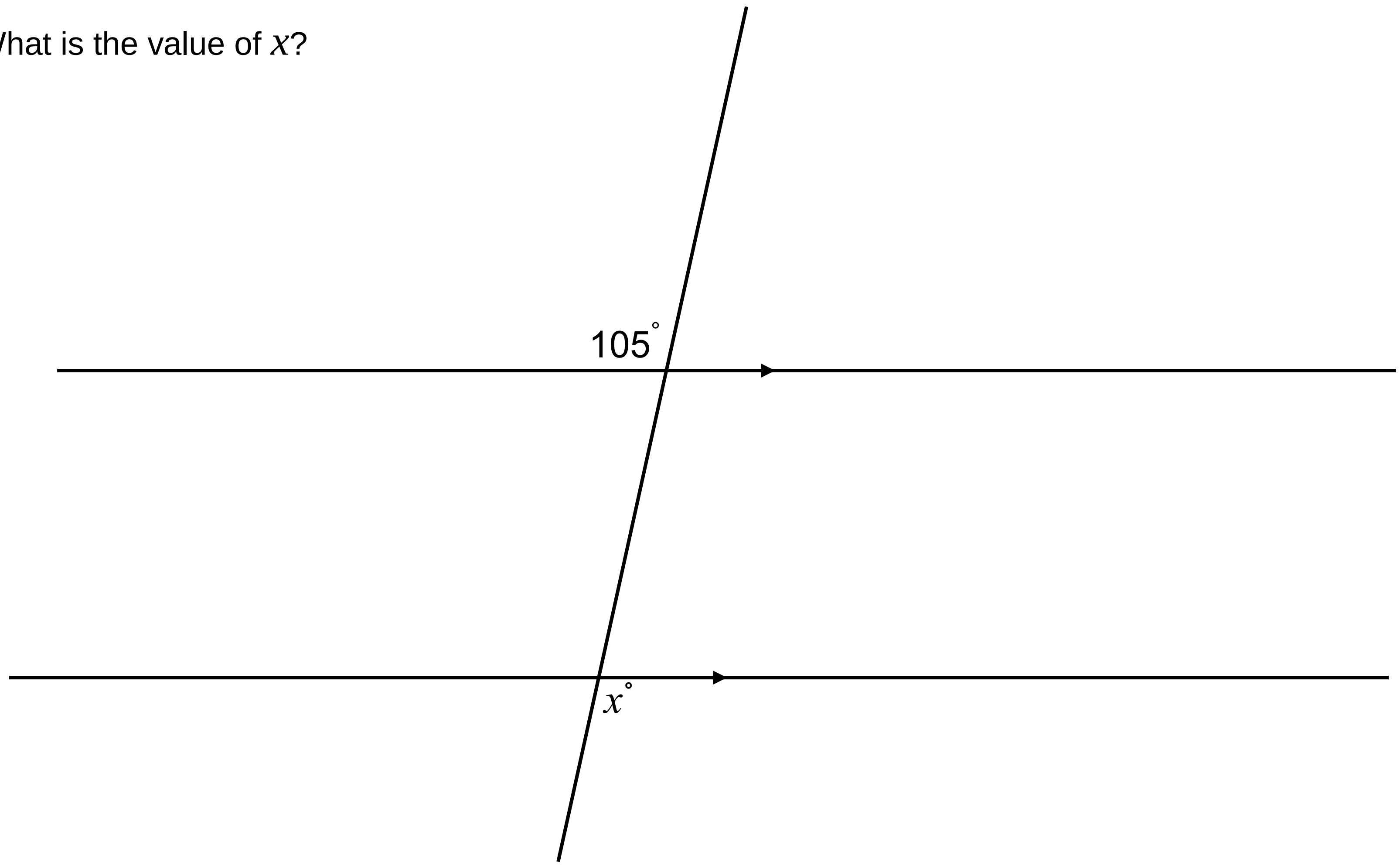
Worked example 1:

Question: What is the value of x?



Practice question 1:

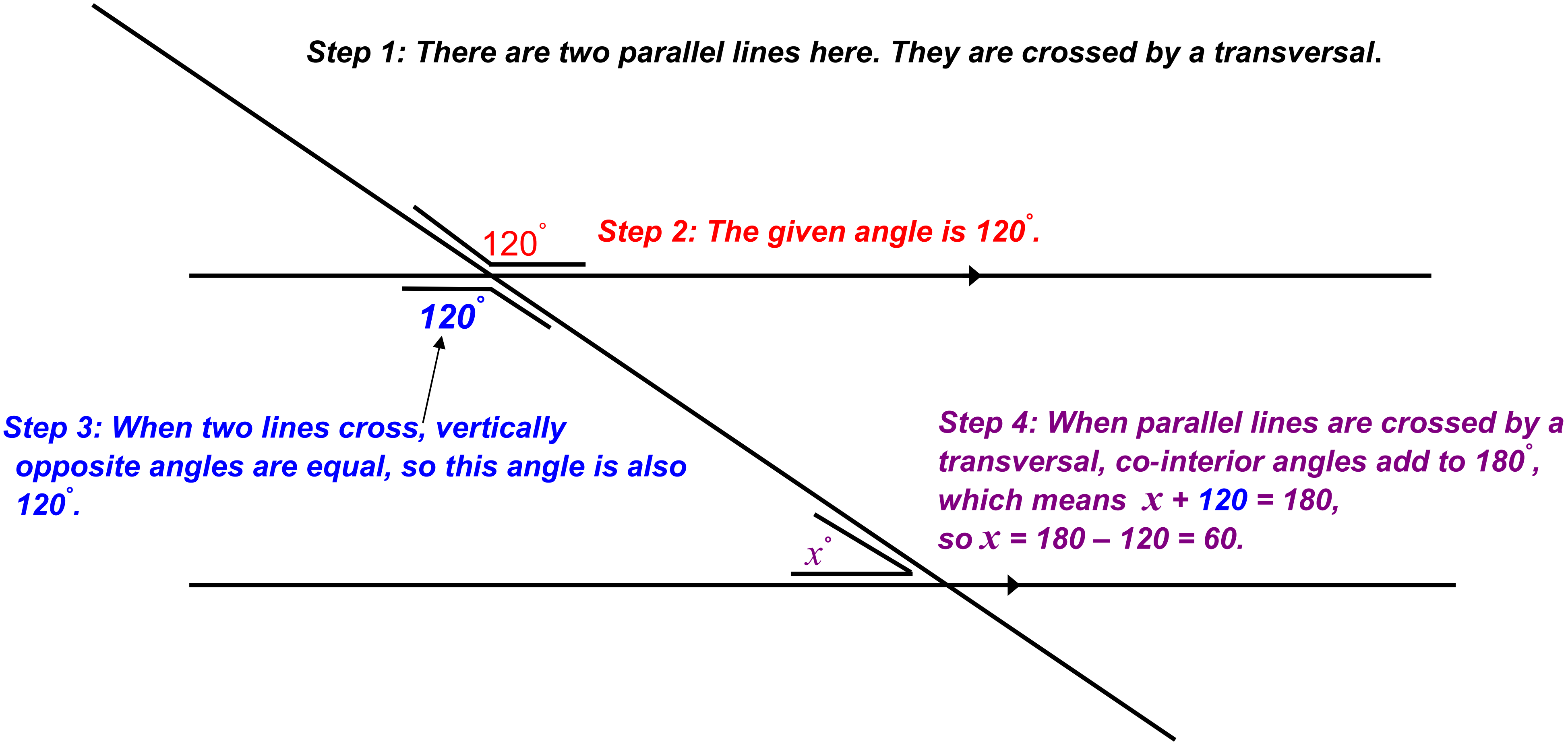
Question: What is the value of x?



Answer: x = __________

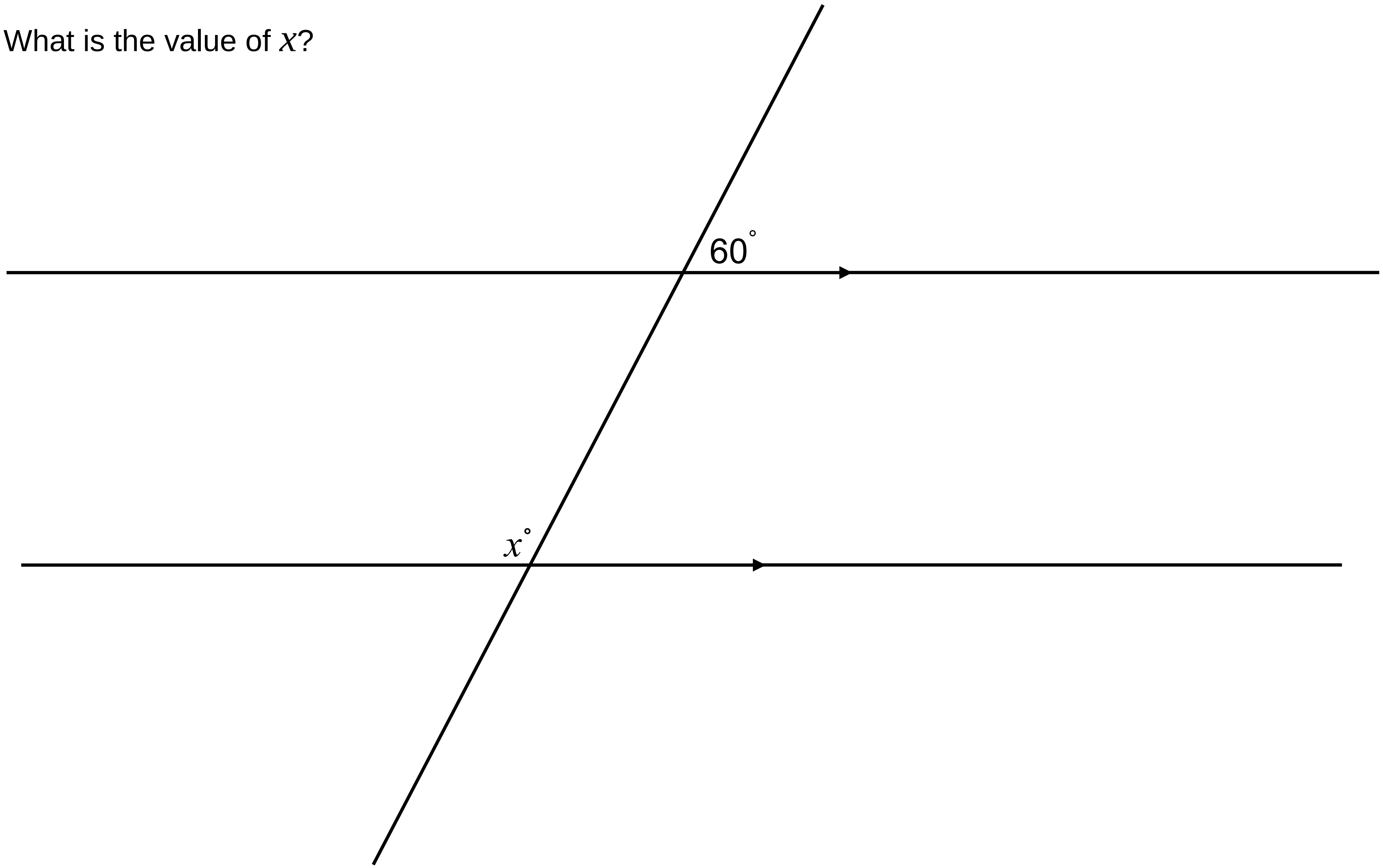
Worked example 2:

Question: What is the value of x?



Practice question 2:

Question: What is the value of x?



Answer: x = __________

Test phase

[Instructions for both groups]

You will now be given 6 problems to solve.

Please apply the angle relationships you have just learned to solve the problems and write down the working for each step to your solution on the diagrams.

You will have up to 60 seconds to solve each problem.

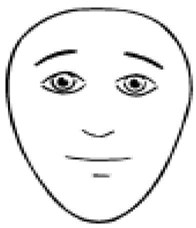
If you work out an incorrect answer, I will tell you and then you can continue trying to work out an answer.

If you have any questions about the test, please ask now.

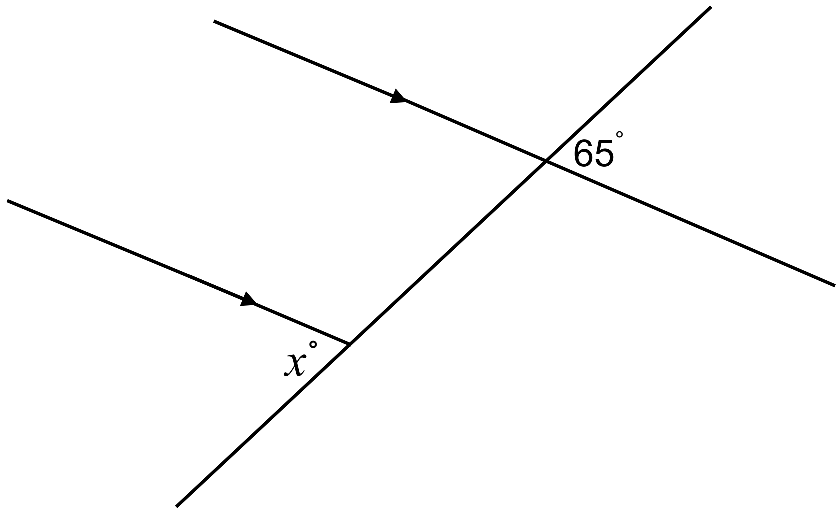
Cognitive Load Ratings (to be collected after each of the questions below)

[Instructions for both groups]

The faces show how people feel when trying to solve a problem. The left-most face shows people find it very easy to solve a problem. The right-most face shows people find it very difficult to solve a problem. After solving each problem, you will be asked how you felt about solving this problem. Please point out if you found the problem very easy, very difficult, or somewhere in the middle.

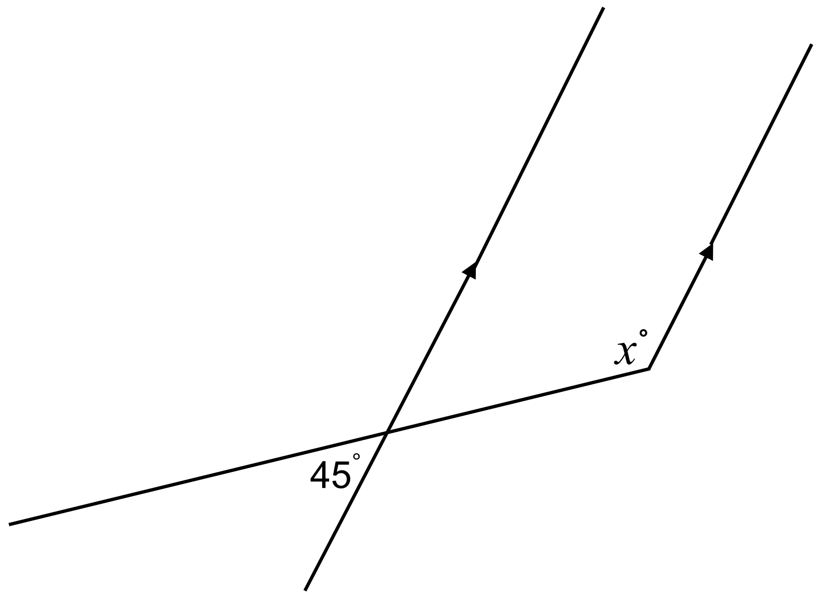
 Very easy 1	2	3	4	 Very difficult 5

Question 1: What is the value of x?



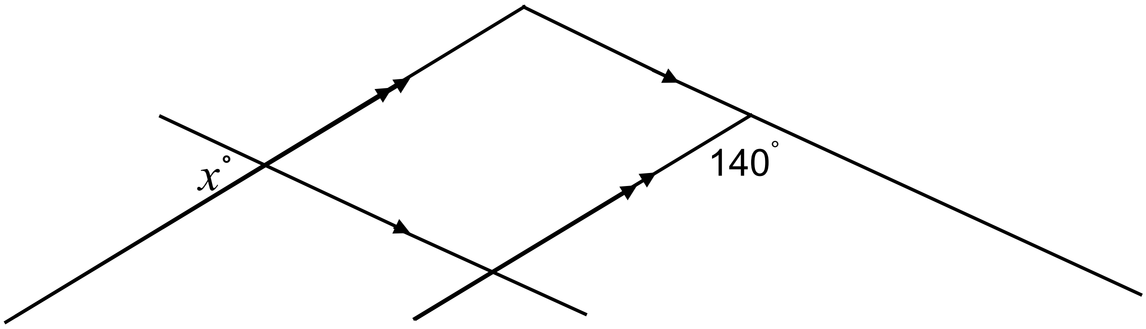
Answer: x = __________

Question 2: What is the value of x?



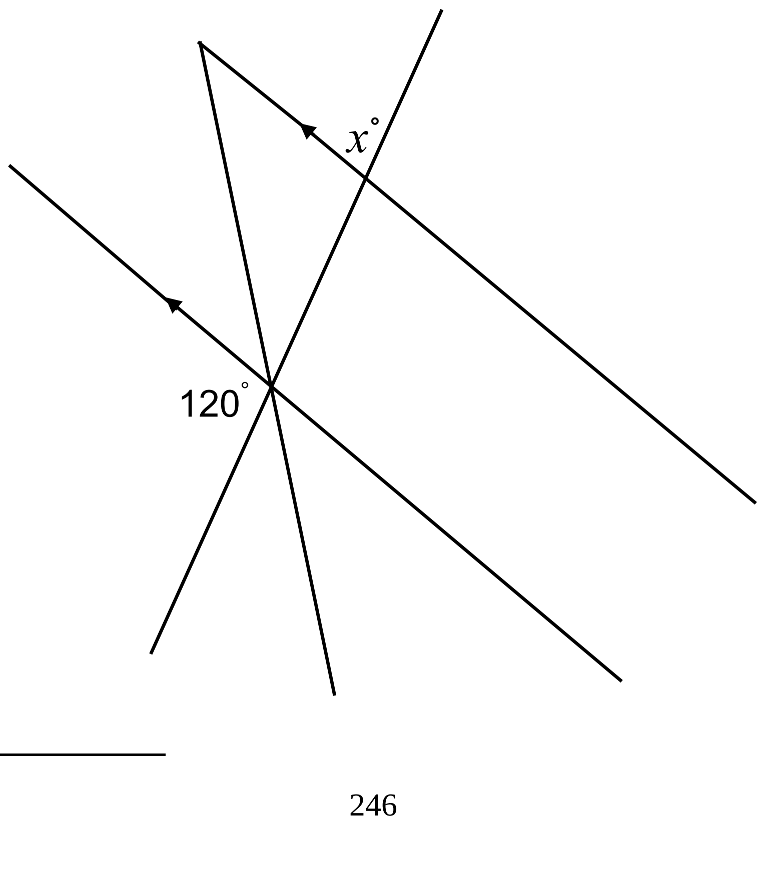
Answer: x = __________

Question 3: What is the value of x?



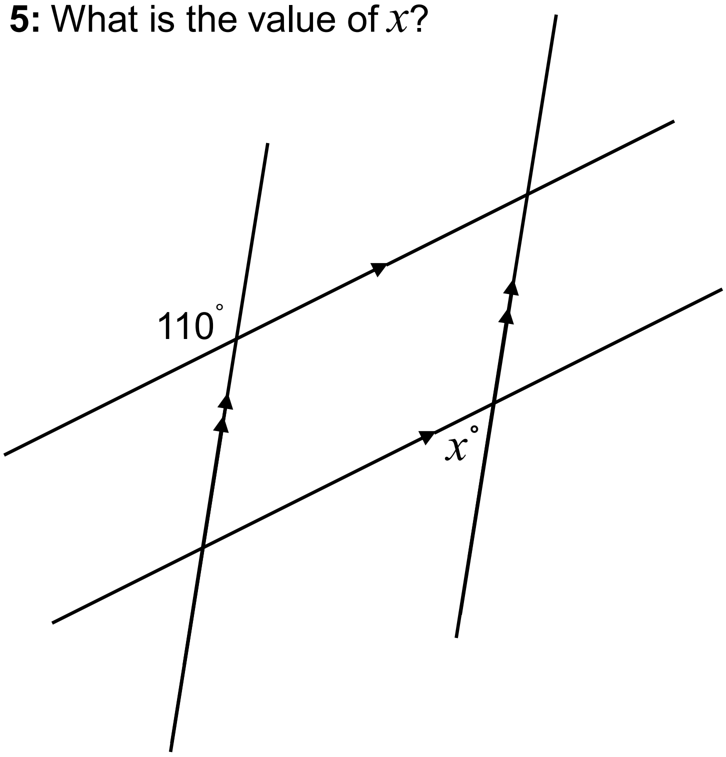
Answer: x = __________

Question 4: What is the value of x?



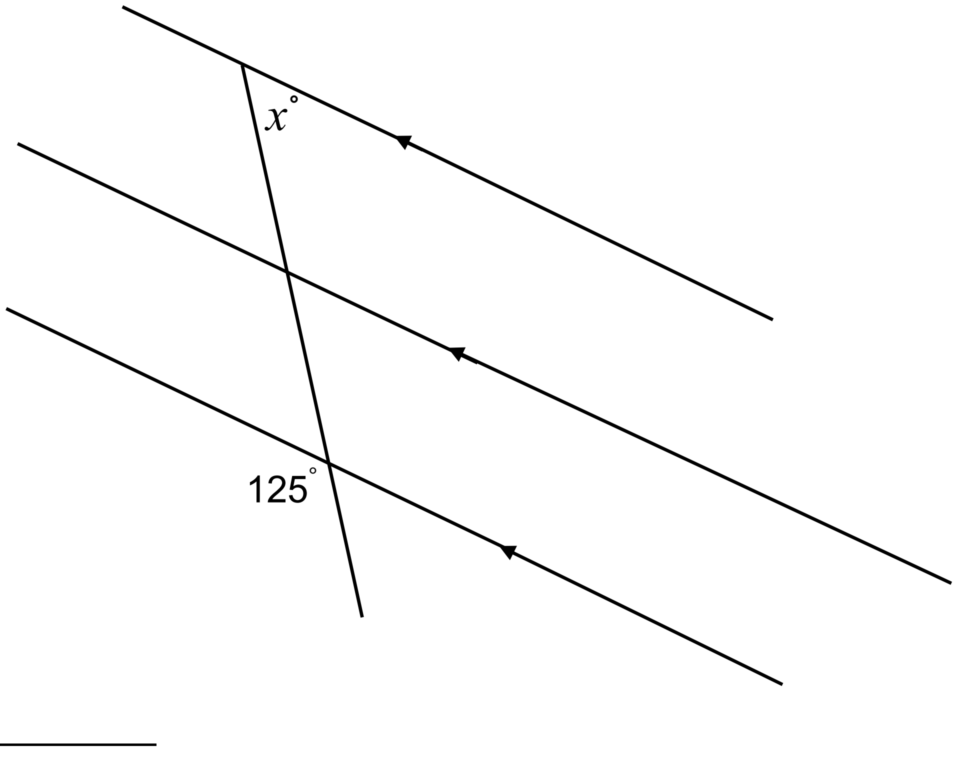
Answer: x = __________

Question 5: What is the value of x?



Answer: x = __________

Question 6: What is the value of x?



Answer: x = __________

Appendix 3: Experimental Materials for Experiment 3

Initial instruction phase

[Instructions for both groups]

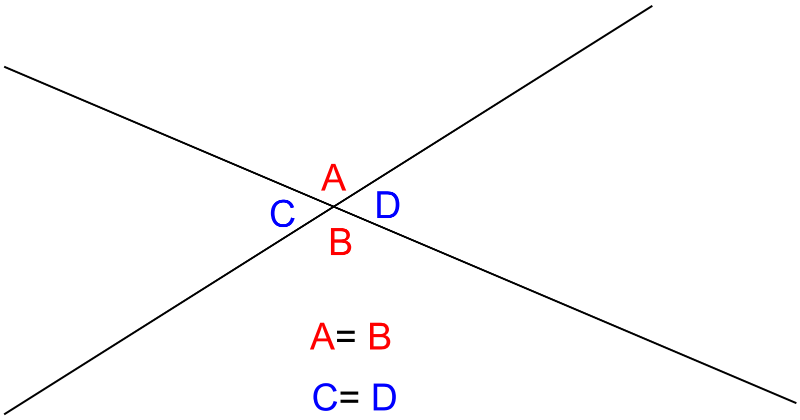
You will now have 2 minutes to study the materials on Angle Relationships on the next 2 pages.

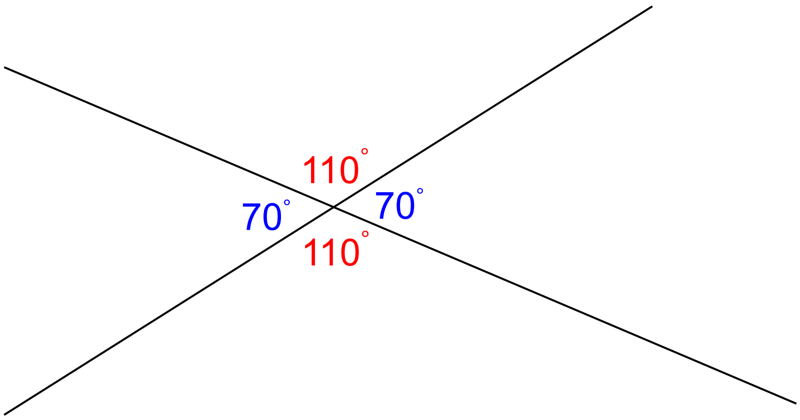
You must read the information carefully and try to understand the information.

If you have read all the pages before the time runs out, please go back to the first page and review the materials you have read.

Angle relationship 1:

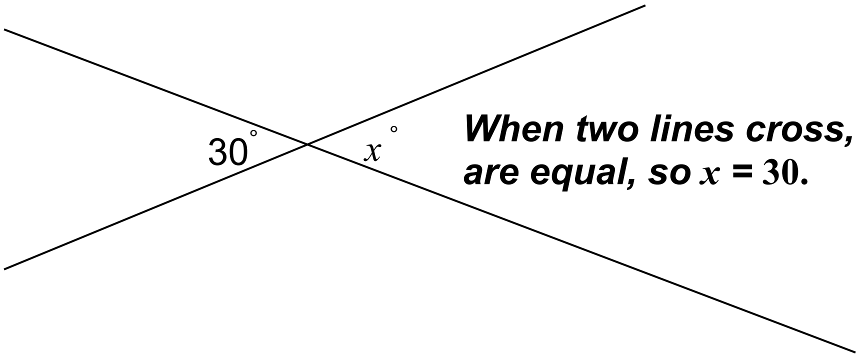
When two lines cross, two pairs of angles vertically opposite each other are formed. The angles in each pair are equal, as in the diagrams.





How to use this relationship

Question: What is the value of x?

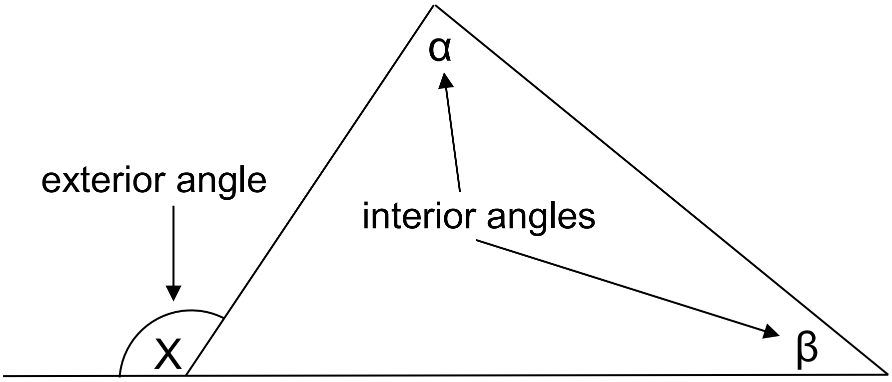


When two lines cross, vertically opposite angles are equal, so $x = 30$.

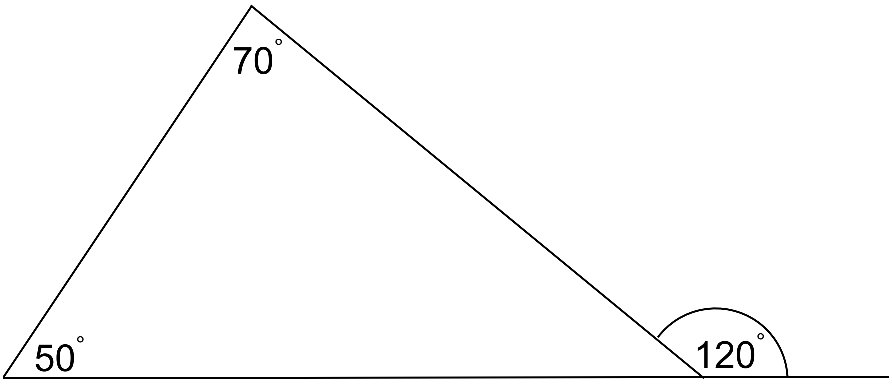
Angle relationship 2:

An exterior angle of a triangle is formed by extending one side of a triangle.

An exterior angle of a triangle is equal to the sum of the two opposite interior angles.



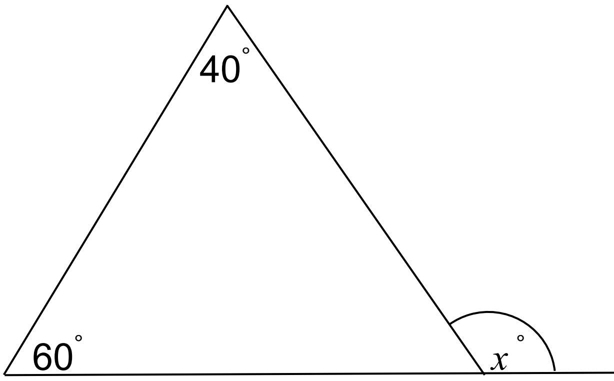
$X = \alpha + \beta$



$120^\circ = 70^\circ + 50^\circ$

How to use this relationship?

Question: What is the value of x?



An exterior angle of a triangle is equal to the sum of the two opposite interior angles, so x = 40 + 60 = 100.

Acquisition phase

[Instructions for the tracing group]

You will now be shown a worked example to study. Please use your index finger of your writing hand to help you learn. You will have 2 minutes to:

(1) Look at the worked example

(2) Read the solution steps in the worked example carefully.

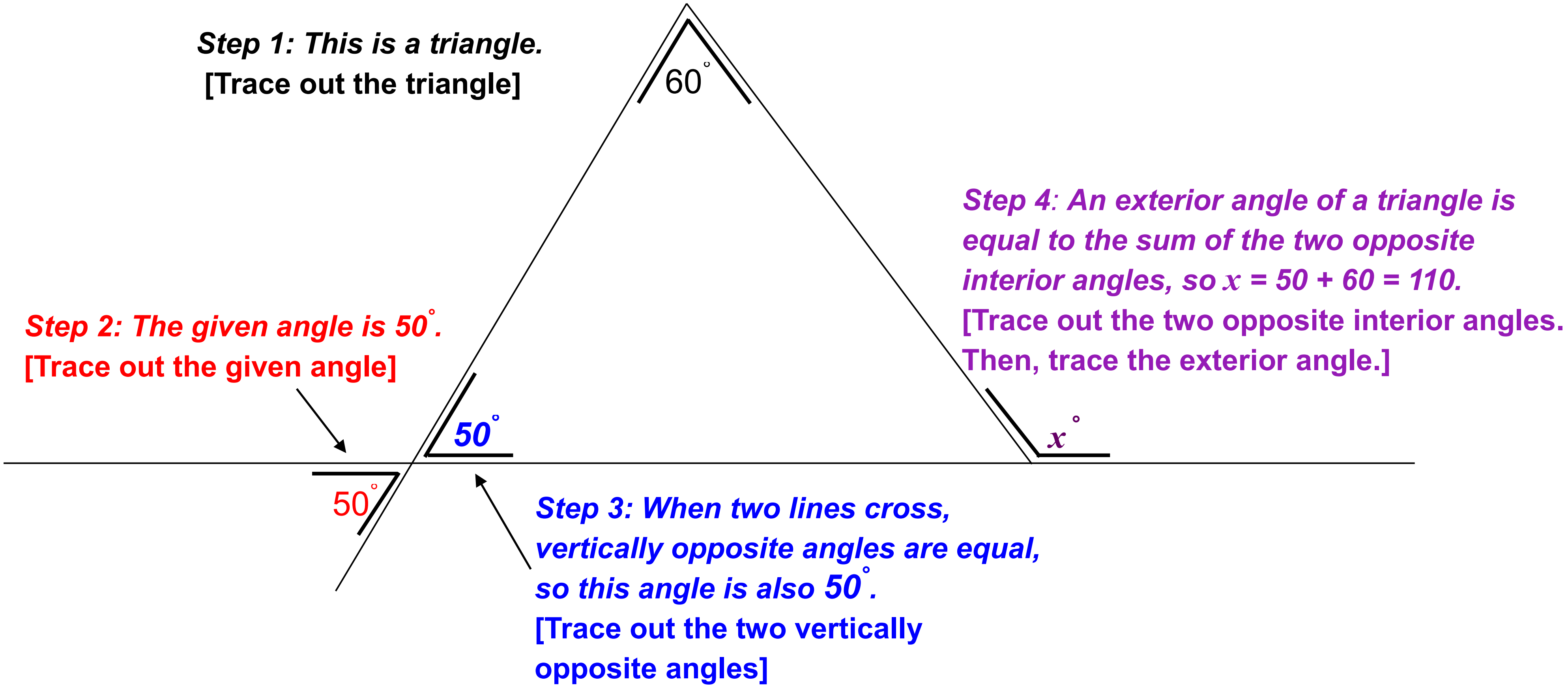
(3) As the instructions in brackets tell you, use your index finger to trace out the diagram on the page.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

Given angles are in normal type; steps of the solution are in ***italic and bold*** type.

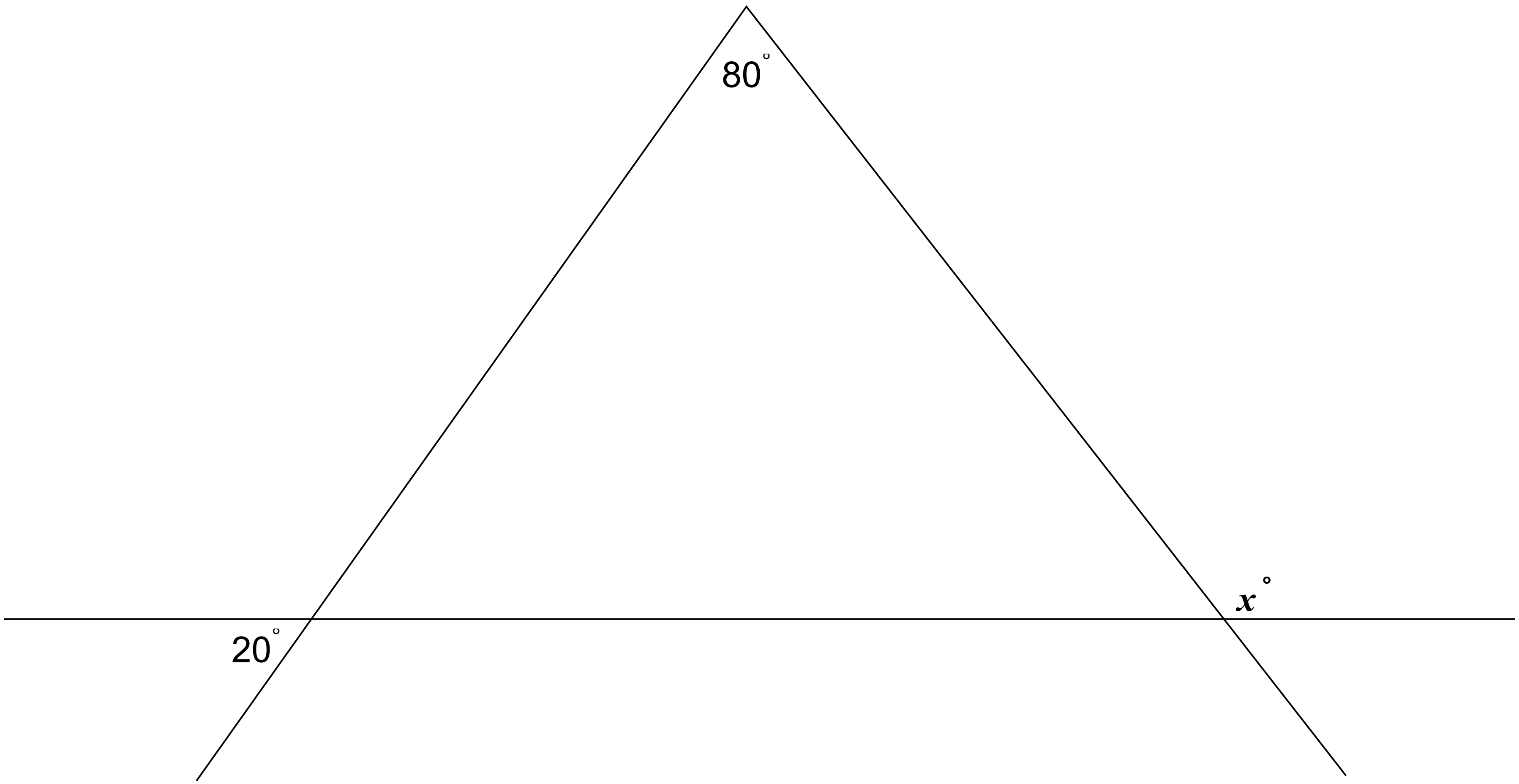
Worked example 1:

Question: What is the value of x?



Practice question 1:

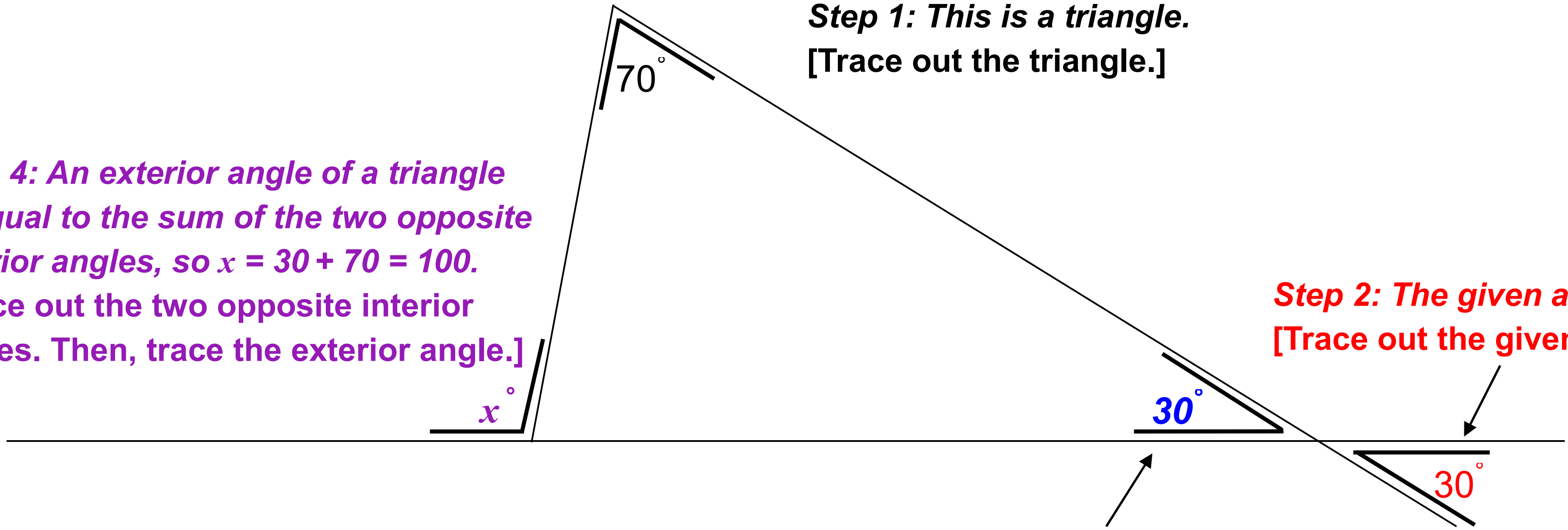
Question: What is the value of x?



Answer: x = __________

Worked example 2:

Question: What is the value of x?



Step 1: This is a triangle.
[Trace out the triangle.]

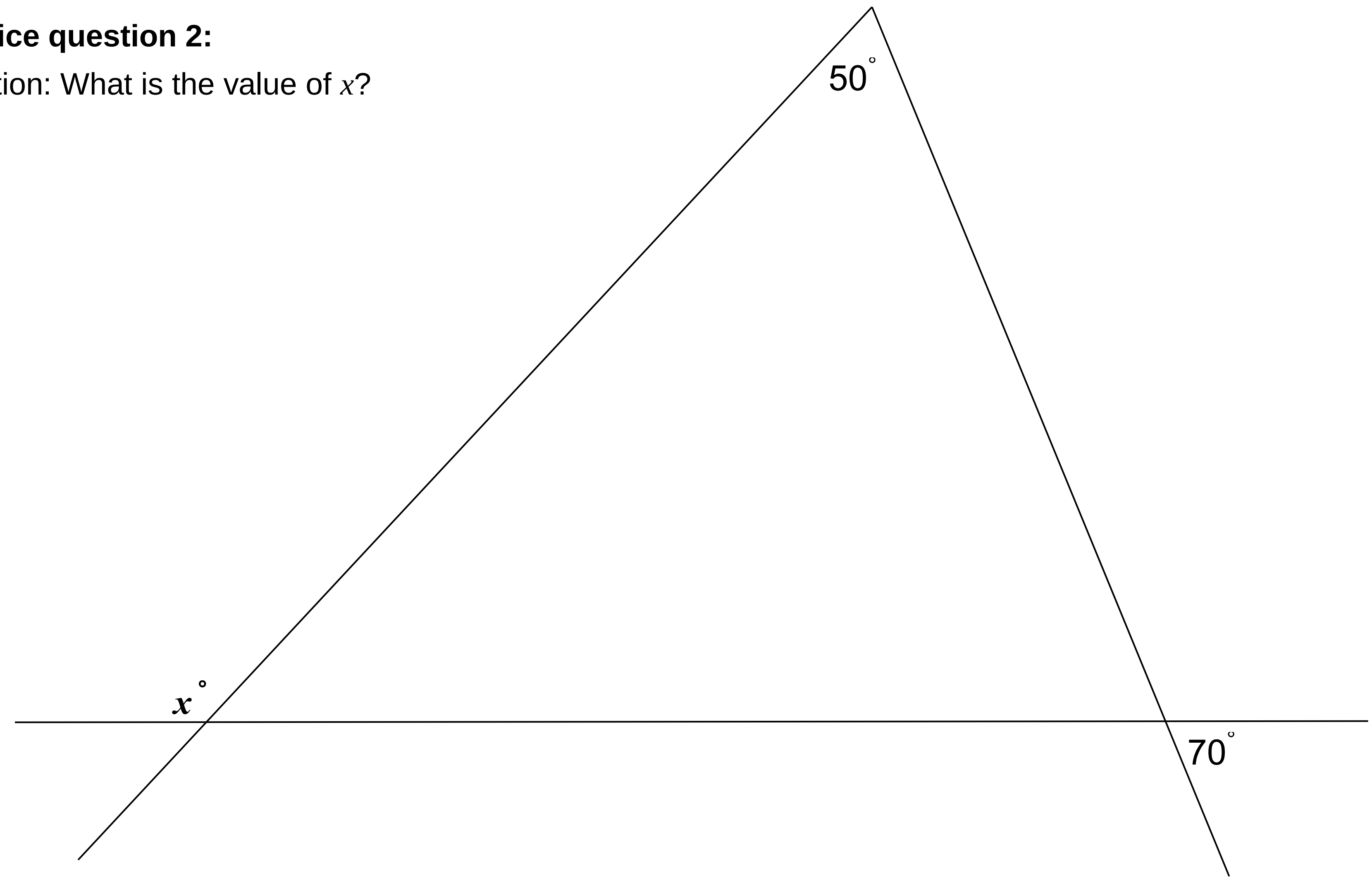
Step 2: The given angle is 30°.
[Trace out the given angle]

Step 3: When two lines cross, vertically opposite angles are equal, so this angle is also 30°. **[Trace out the two vertically opposite angles]**

Step 4: An exterior angle of a triangle is equal to the sum of the two opposite interior angles, so $x = 30 + 70 = 100$.
[Trace out the two opposite interior angles. Then, trace the exterior angle.]

Practice question 2:

Question: What is the value of x?



Answer: x = __________

Acquisition phase

[Instructions for the non-tracing group]

You will now be shown a worked example to study. Please use your index finger of your writing hand to help you learn. You will have 2 minutes to:

(1) Look at the worked example

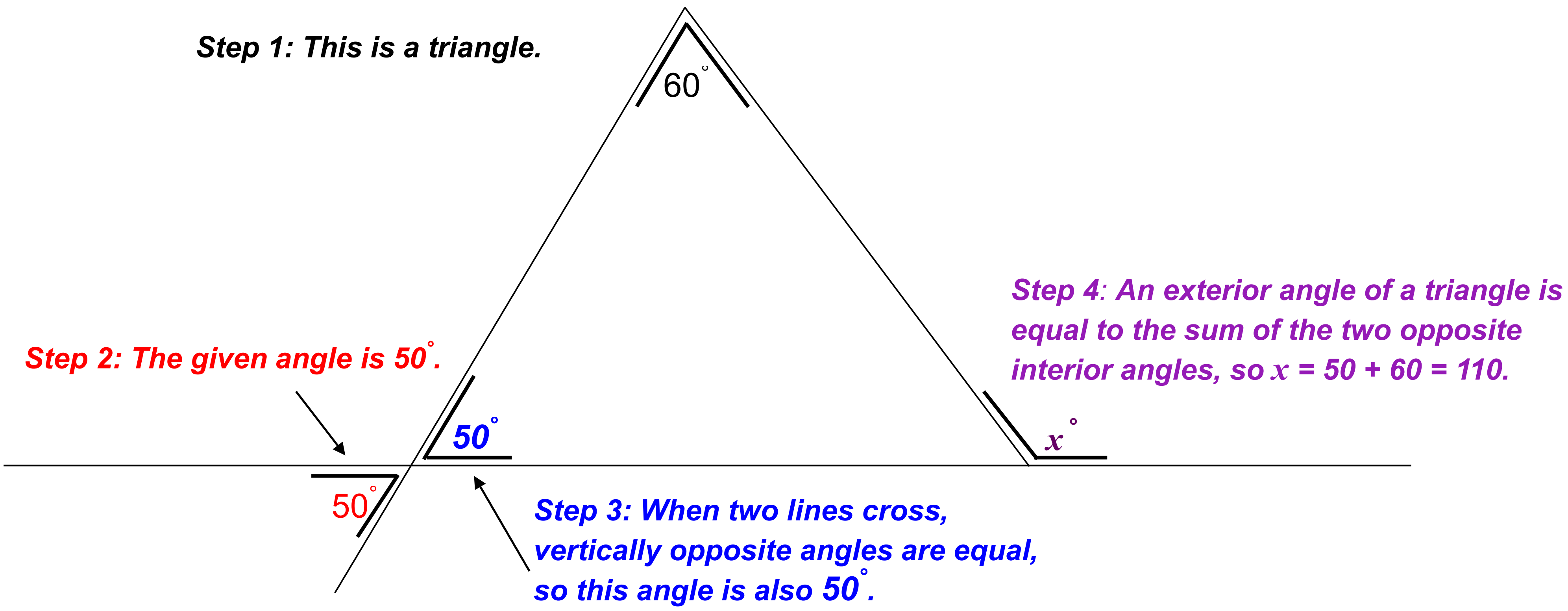
(2) Read the solution steps in the worked example carefully.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

Given angles are in normal type; steps of the solution are in ***italic and bold*** type.

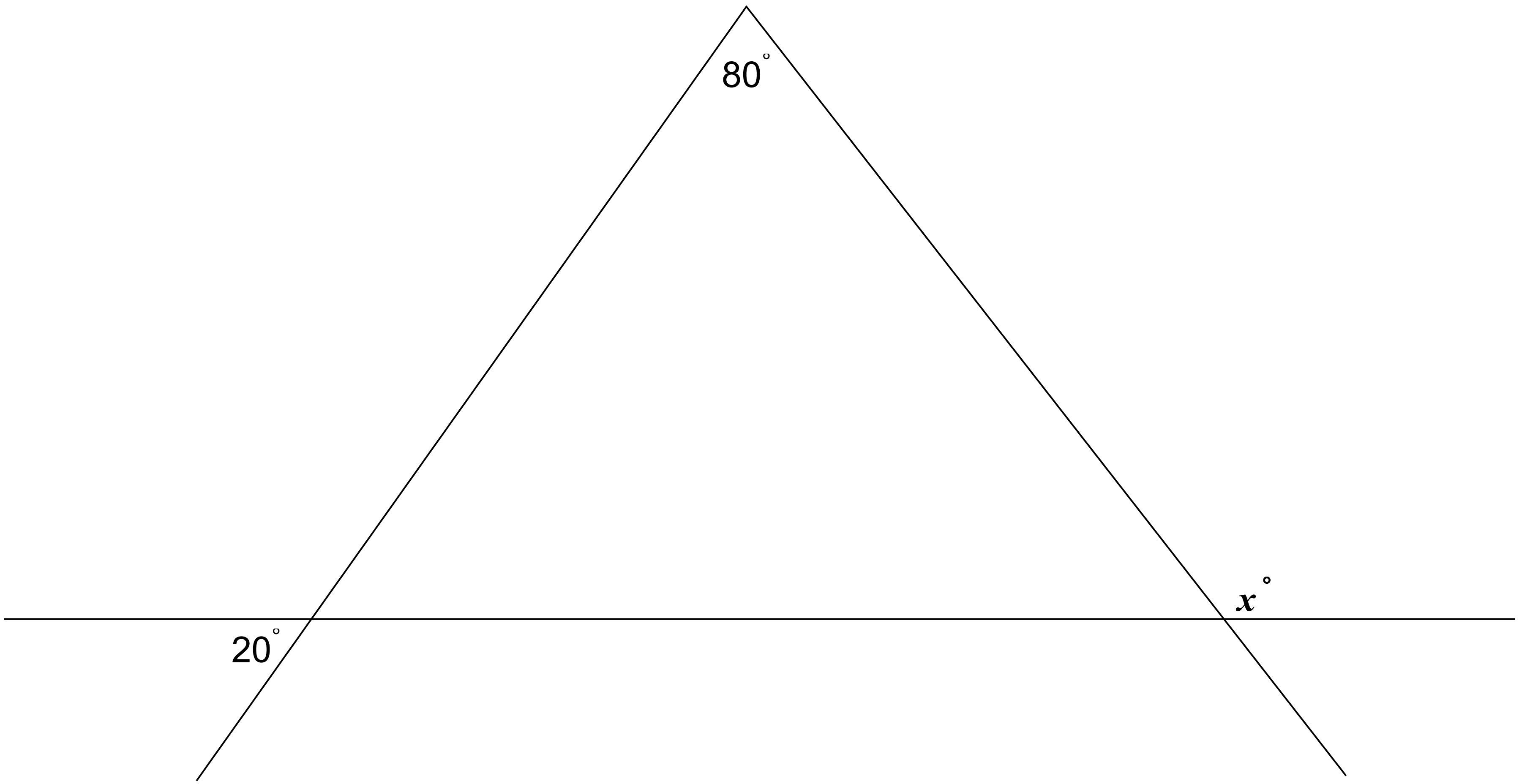
Worked example 1:

Question: What is the value of x?



Practice question 1:

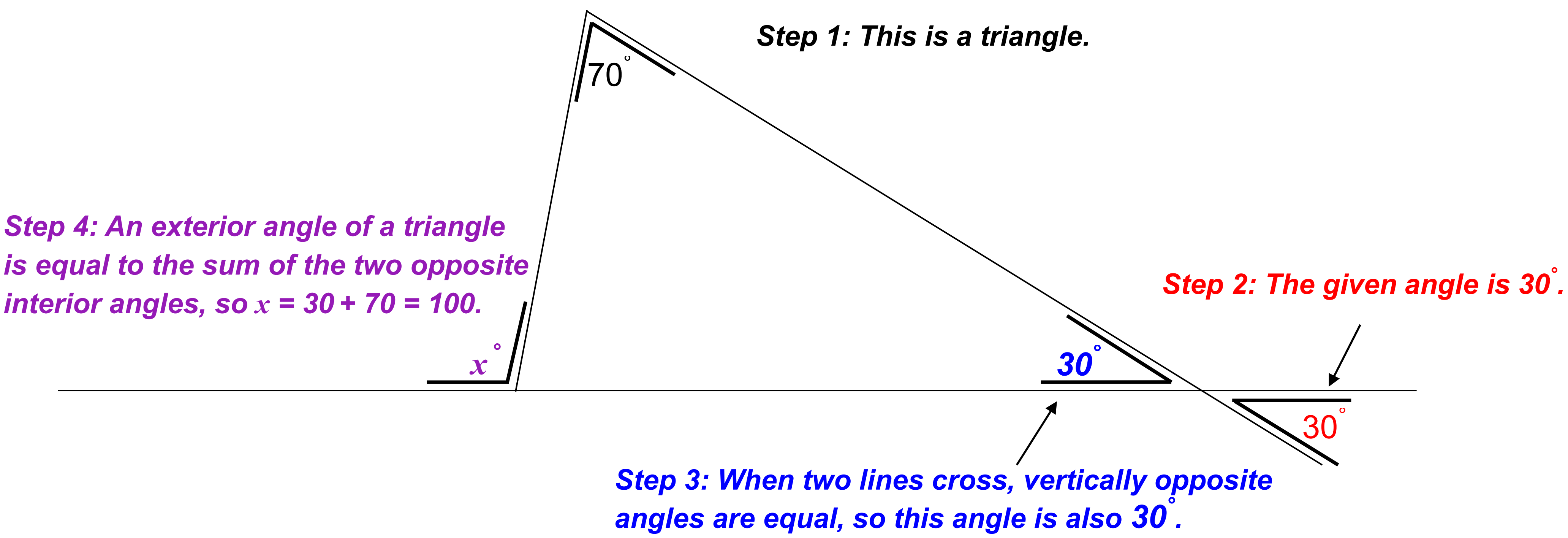
Question: What is the value of x?



Answer: x = __________

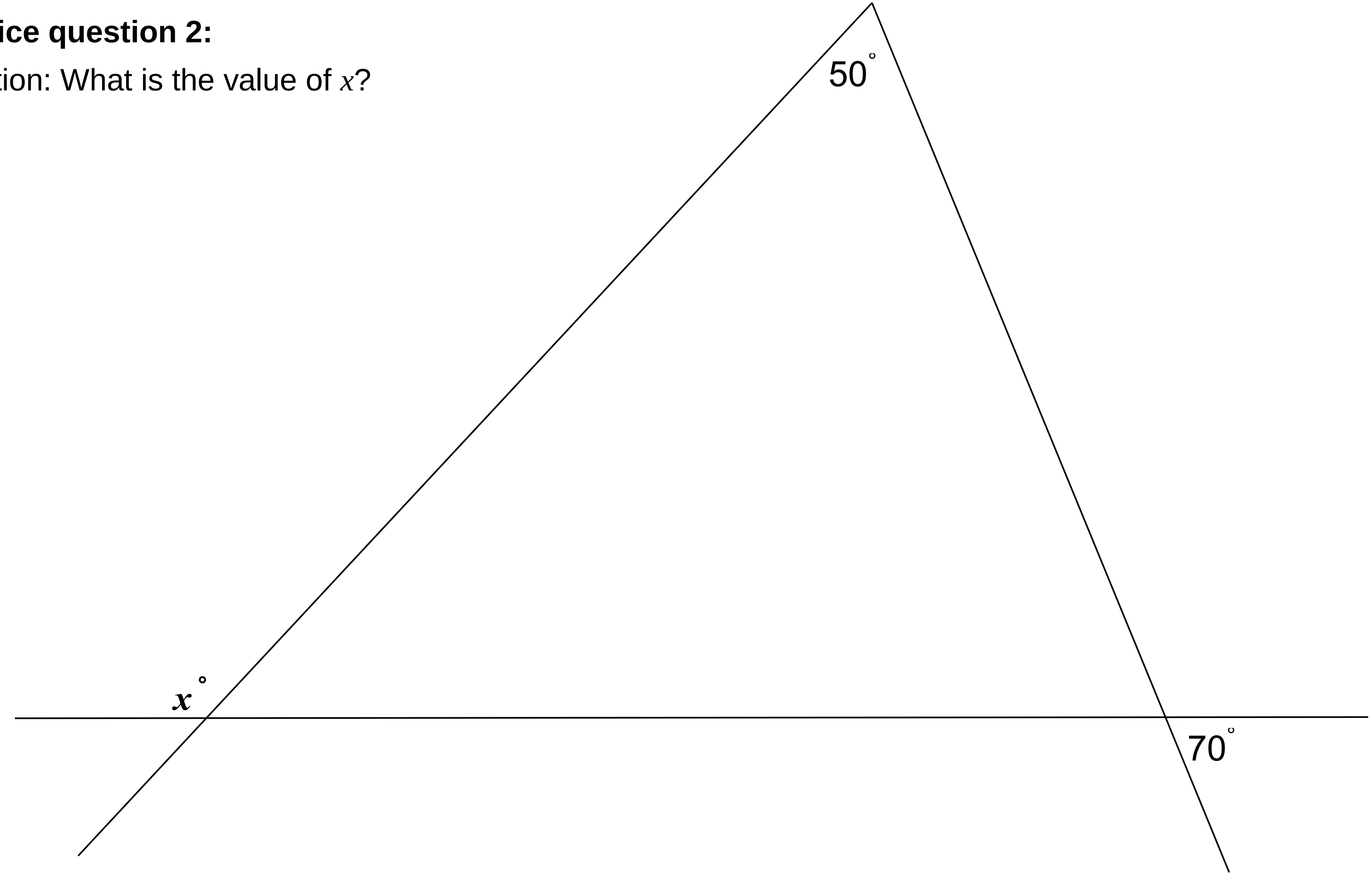
Worked example 2:

Question: What is the value of x?



Practice question 2:

Question: What is the value of x?



Answer: x = __________

Test phase

[Instructions for both groups]

You will now be given 6 problems to solve.

Please apply the angle relationships you have just learned to solve the problems and write down the working for each step to your solution on the diagrams.

You will have up to 60 seconds to solve each problem.

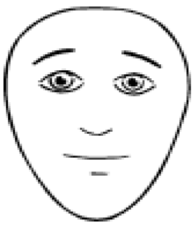
If you work out an incorrect answer, I will tell you and then you can continue trying to work out an answer.

If you have any questions about the test, please ask now.

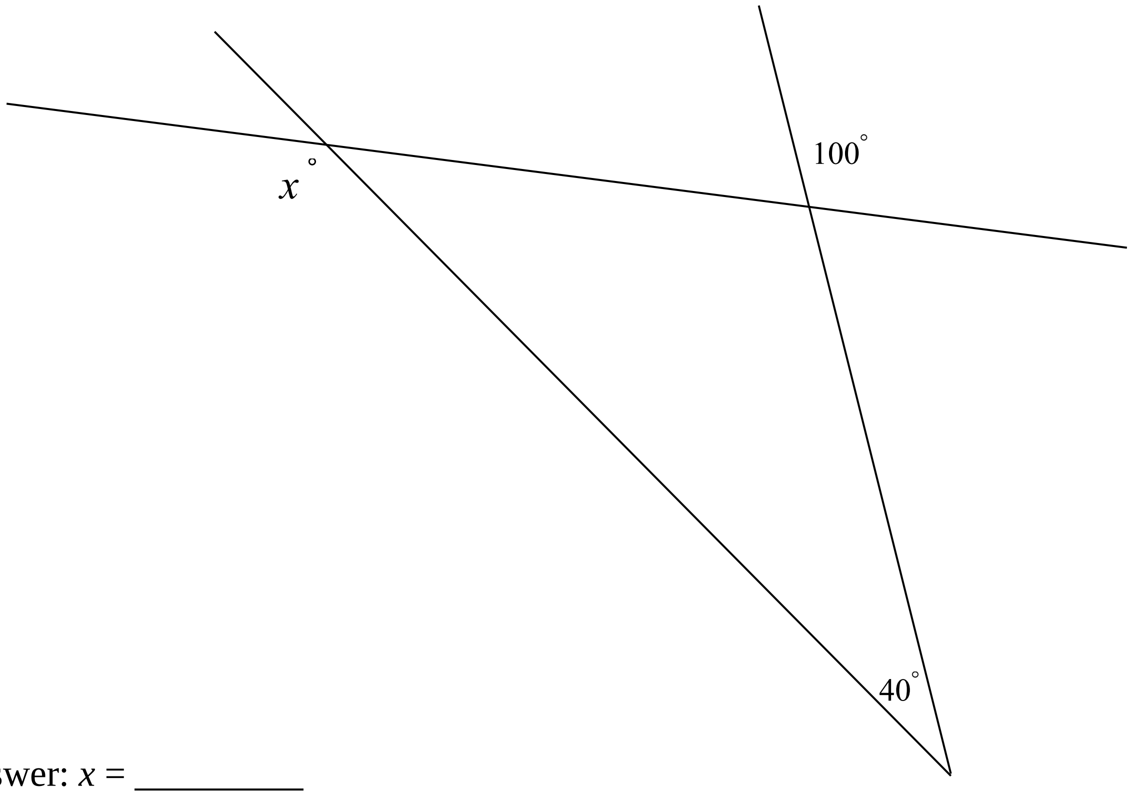
Cognitive Load Ratings (to be collected after each of the questions below)

[Instructions for both groups]

The faces show how people feel when trying to solve a problem. The left-most face shows people find it very easy to solve a problem. The right-most face shows people find it very difficult to solve a problem. After solving each problem, you will be asked how you felt about solving this problem. Please point out if you found the problem very easy, very difficult, or somewhere in the middle.

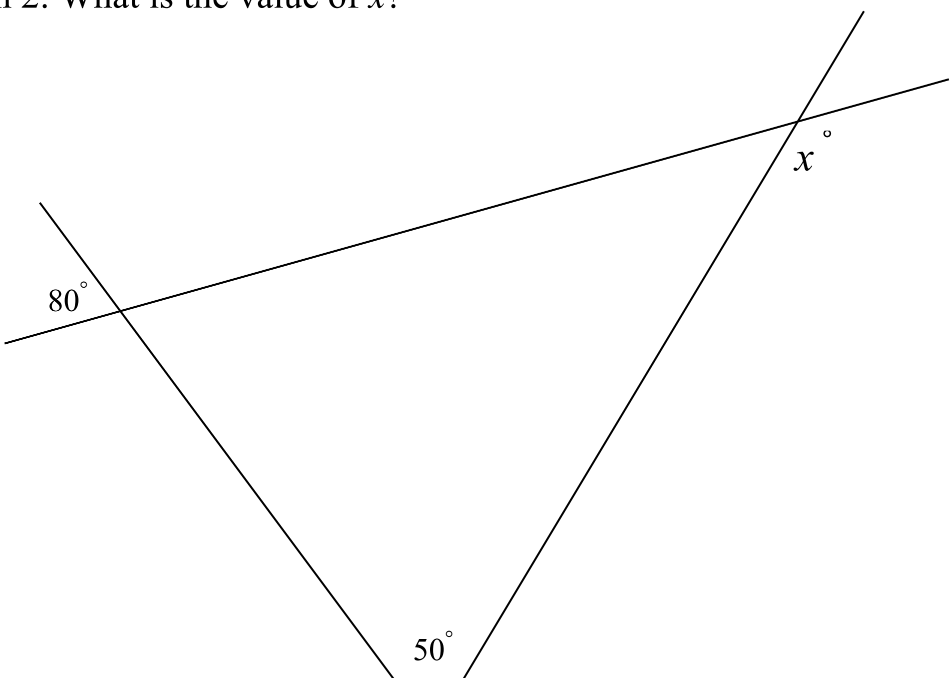
 Very easy				 Very difficult
1	2	3	4	5

Question 1: What is the value of *x*?



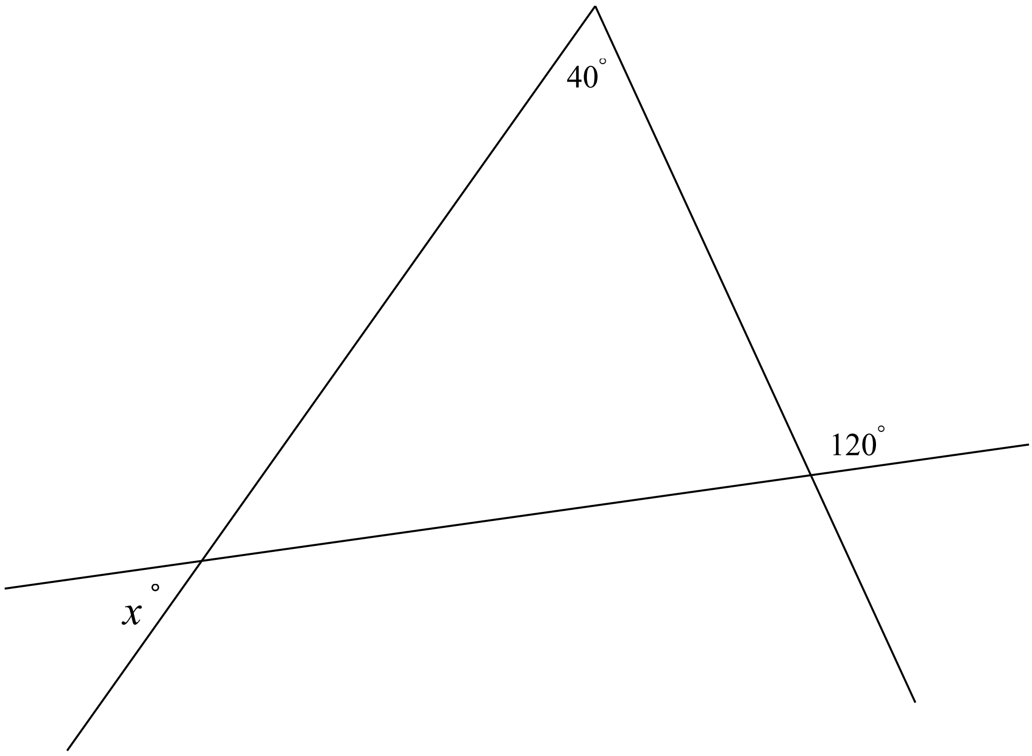
Answer: *x* = __________

Question 2: What is the value of *x*?



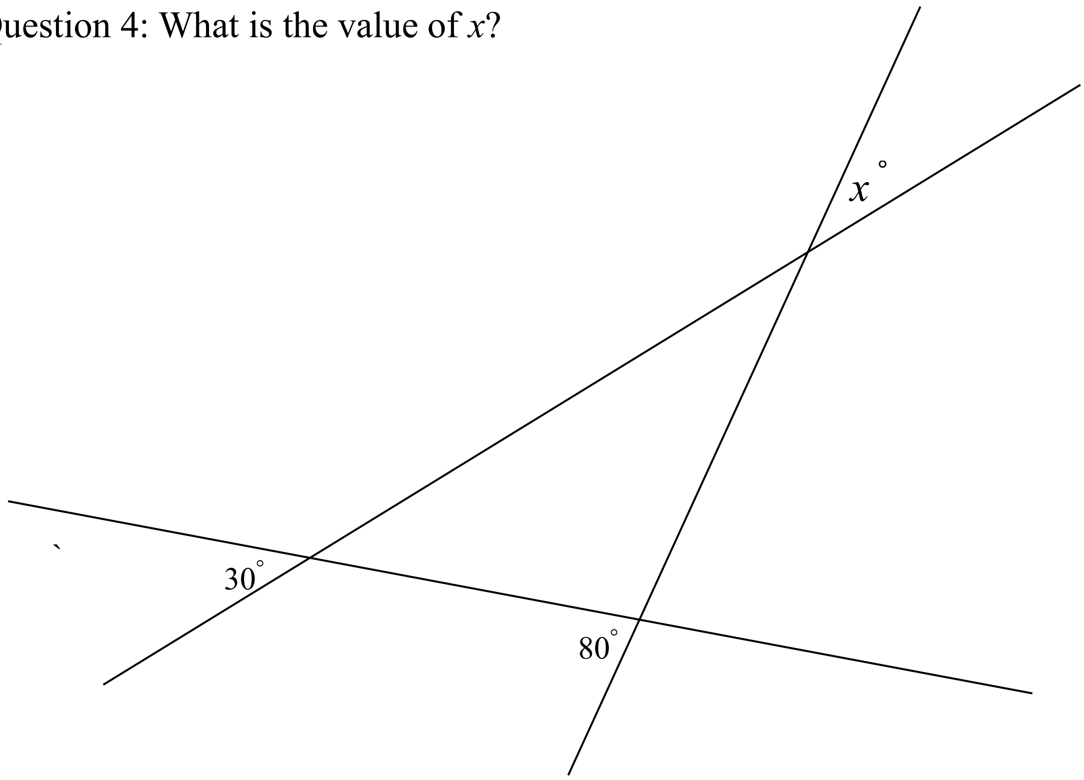
Answer: *x* = __________

Question 3: What is the value of *x*?



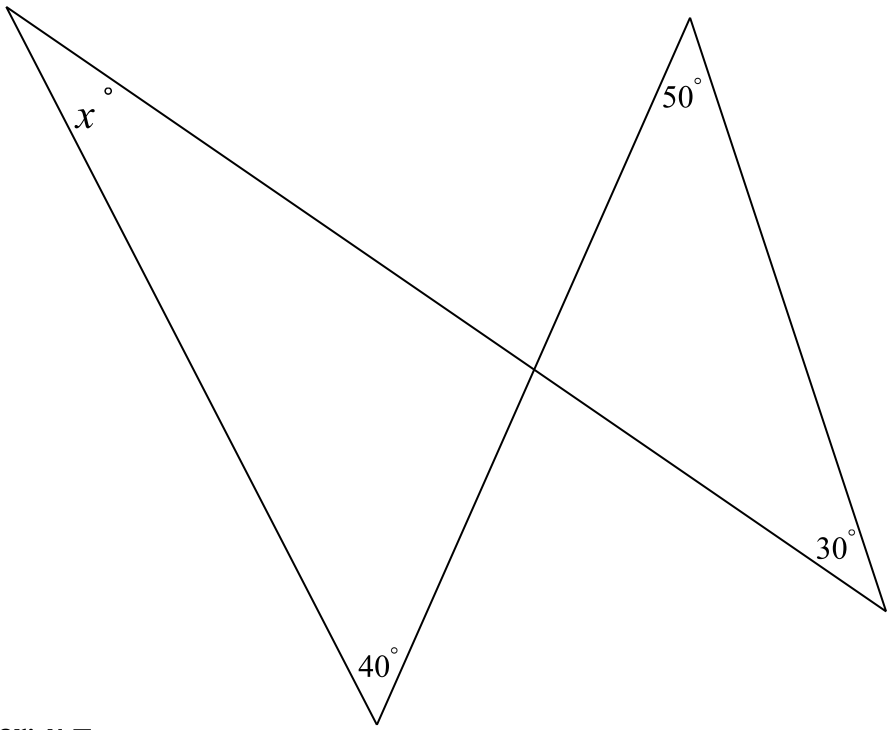
Answer: *x* = __________

Question 4: What is the value of *x*?



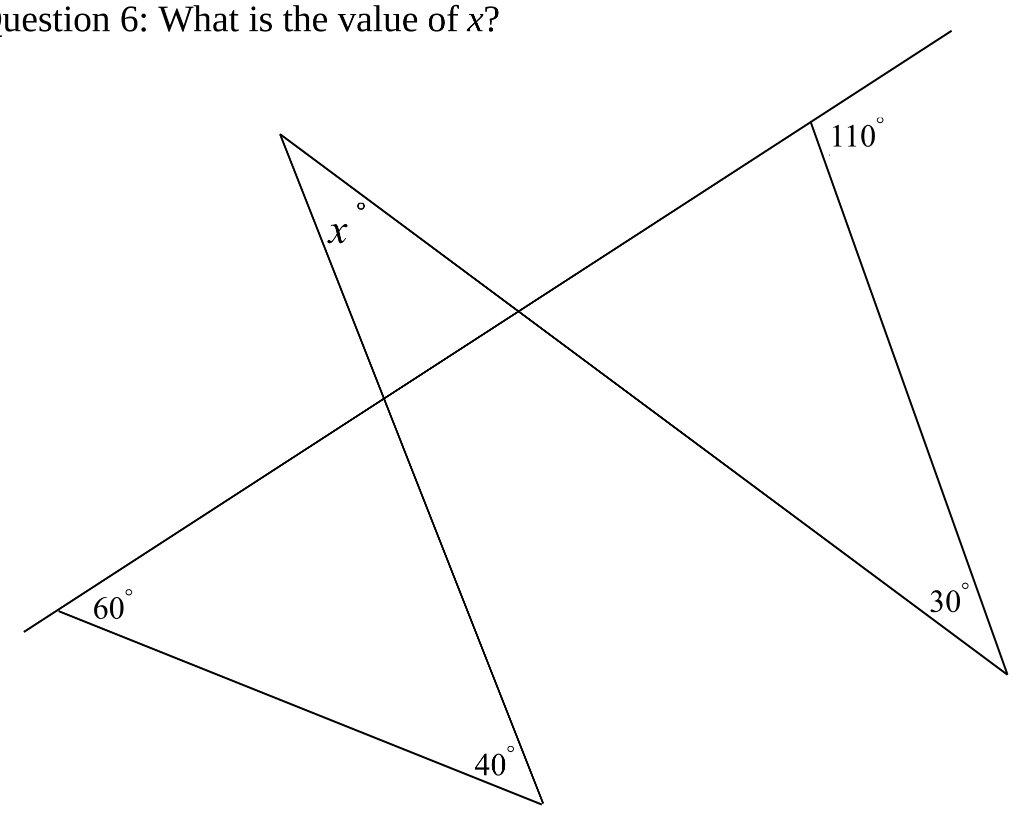
Answer: *x* = __________

Question 5: What is the value of *x*?



Answer: *x* = __________

Question 6: What is the value of *x*?



Answer: *x* = __________

Appendix 4: Experimental Materials for Experiment 4

Initial instruction phase

[Instructions for both groups]

You will now have 5 minutes to study the materials on Angle Relationships on the next 5 pages.

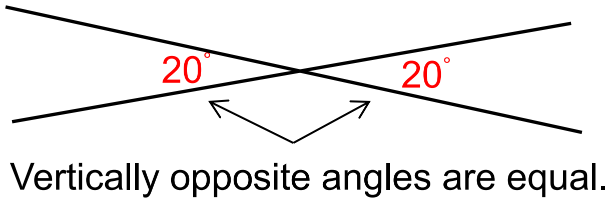
You must read the information carefully and try to understand the information.

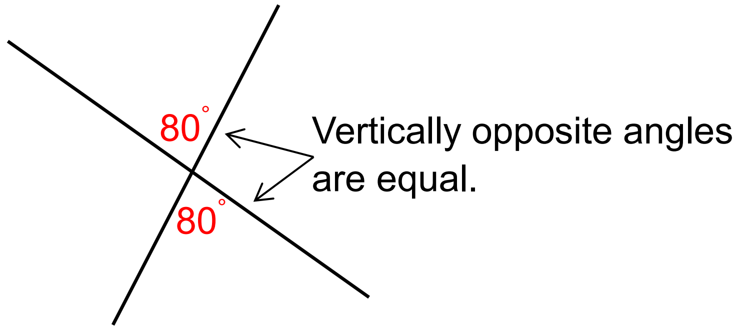
If you have read all the pages before the time runs out, please go back to the first page and review the materials you have read.

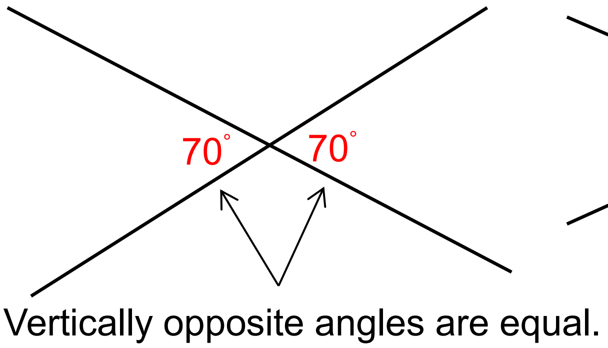
Angle relationship 1:

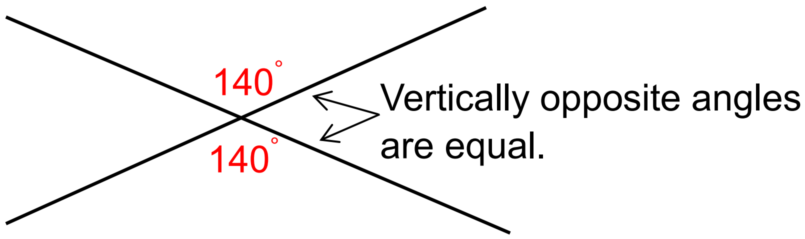
Vertically opposite angles

When two lines cross, the angles vertically opposite each other are equal.



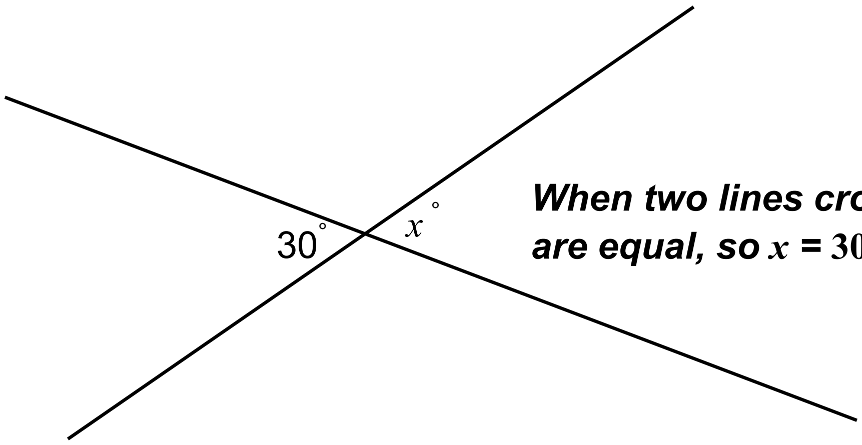






How to use this relationship

Question: What is the value of x?

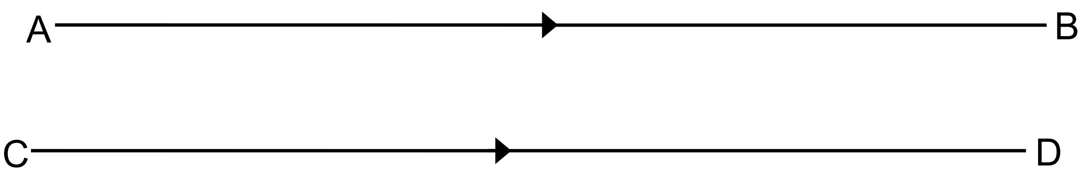


When two lines cross, vertically opposite angles are equal, so $x = 30$.

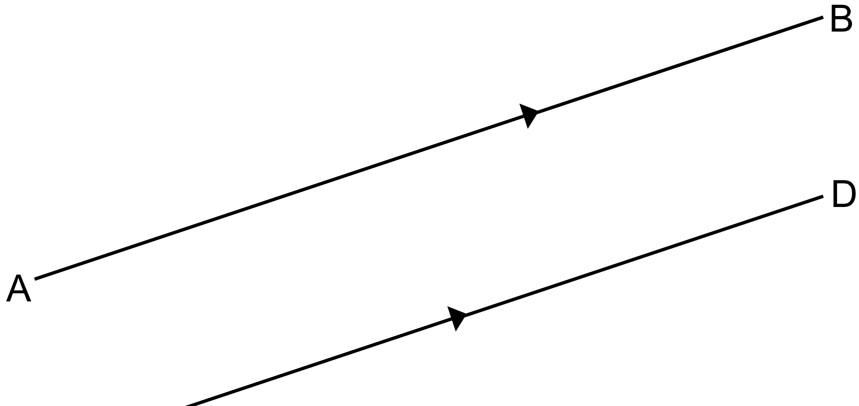
Parallel lines

If two lines point in the same direction and will never cross, the two lines are parallel.

To show the lines are parallel, small arrow marks are noted on the lines, as in these diagrams.

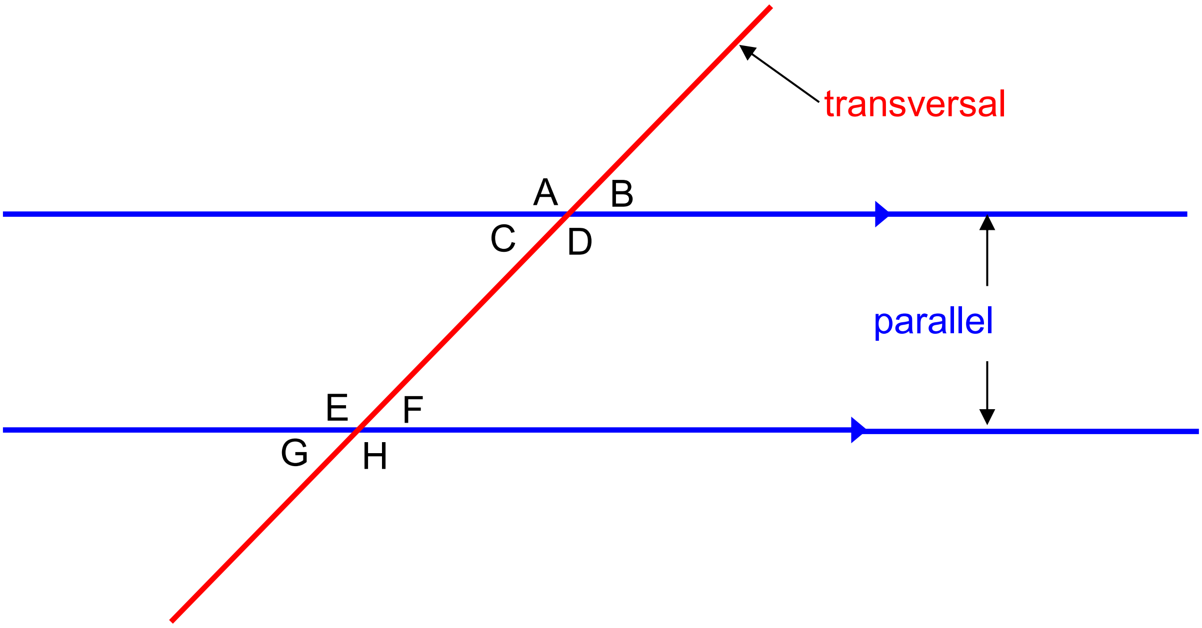


The line AB is parallel to the line CD.



The line AB is parallel to the line CD.

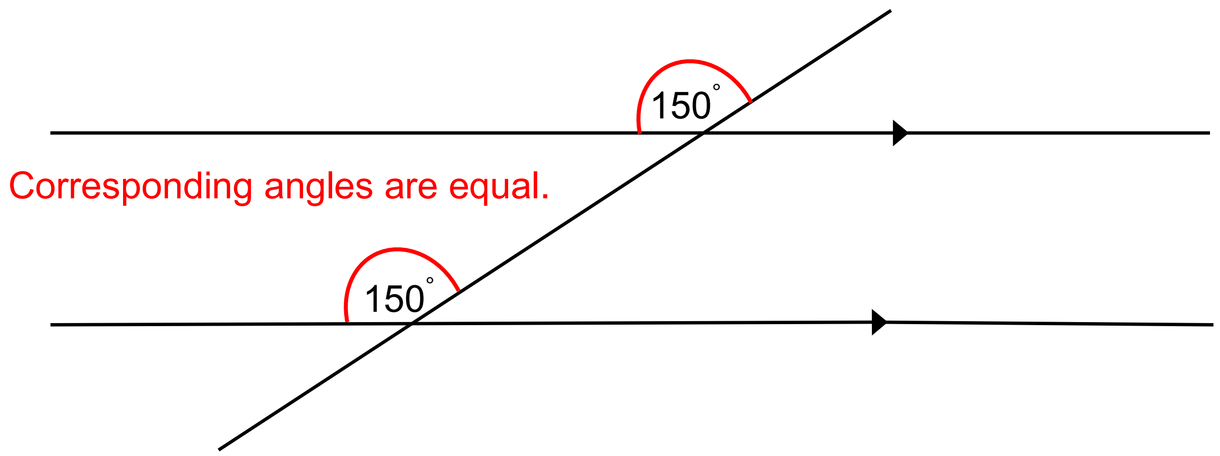
When parallel lines are crossed by another line (which is called a transversal), several angles (for example, A, B, C, D, E, F, G, H) are formed.

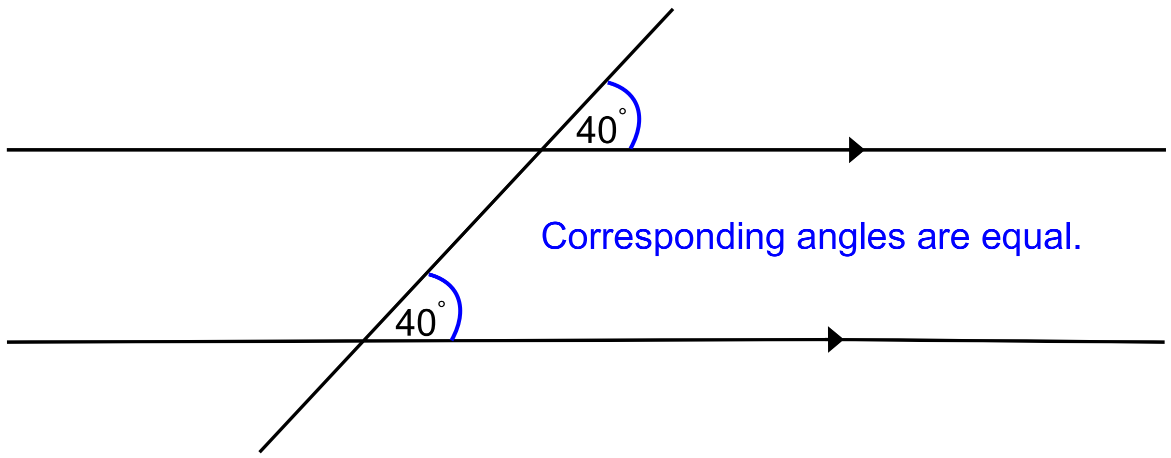


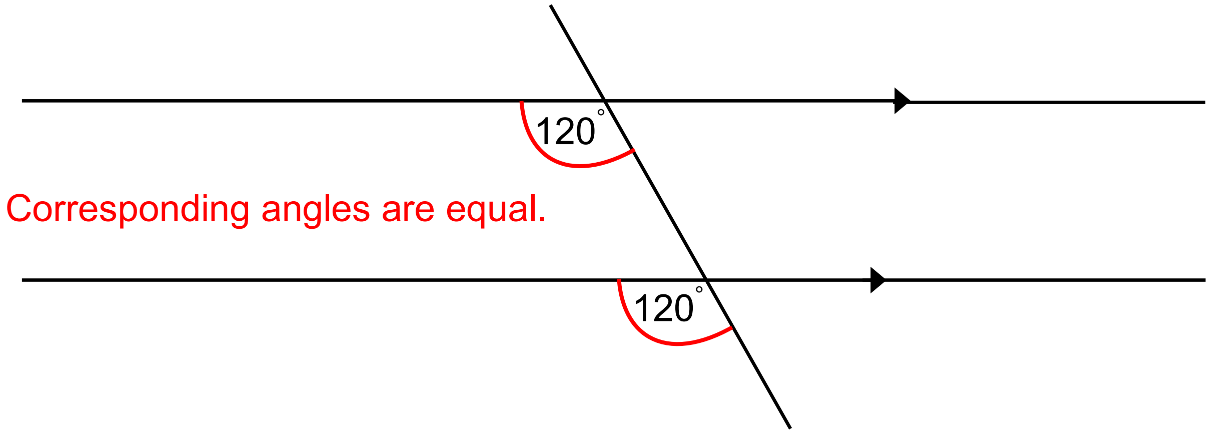
Angle relationship 2:

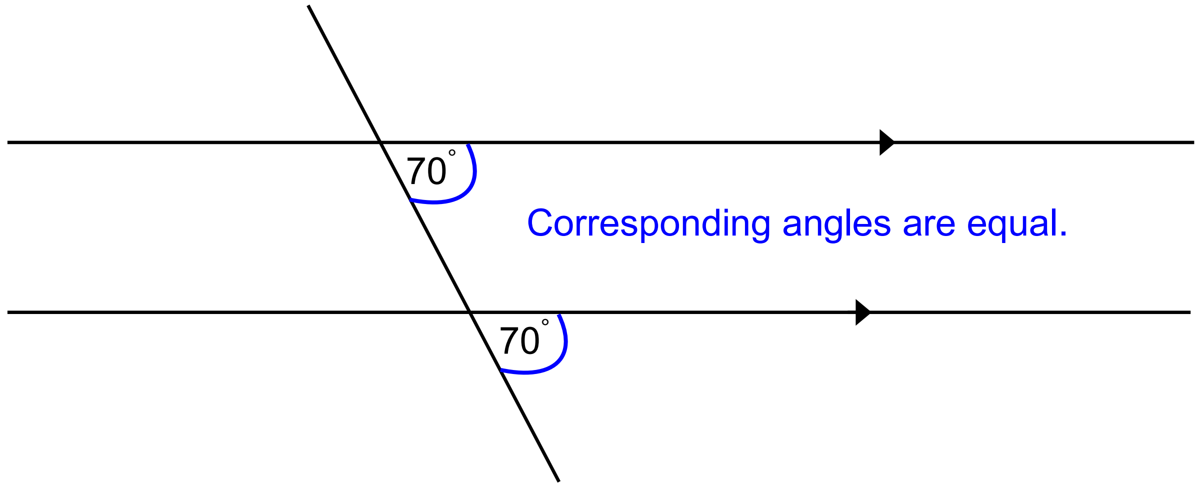
Corresponding angles

When parallel lines are crossed by a transversal, the angles at matching locations are equal.



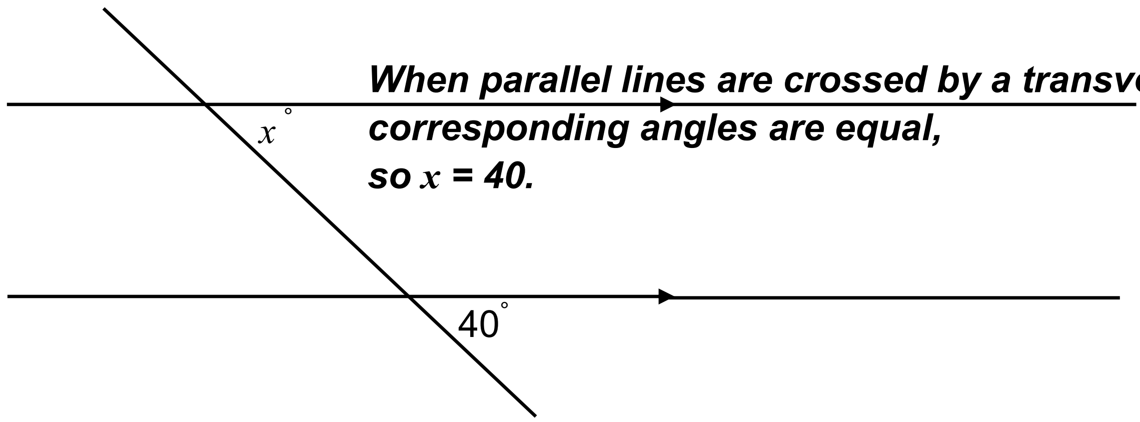






How to use this relationship

Question: What is the value of x?

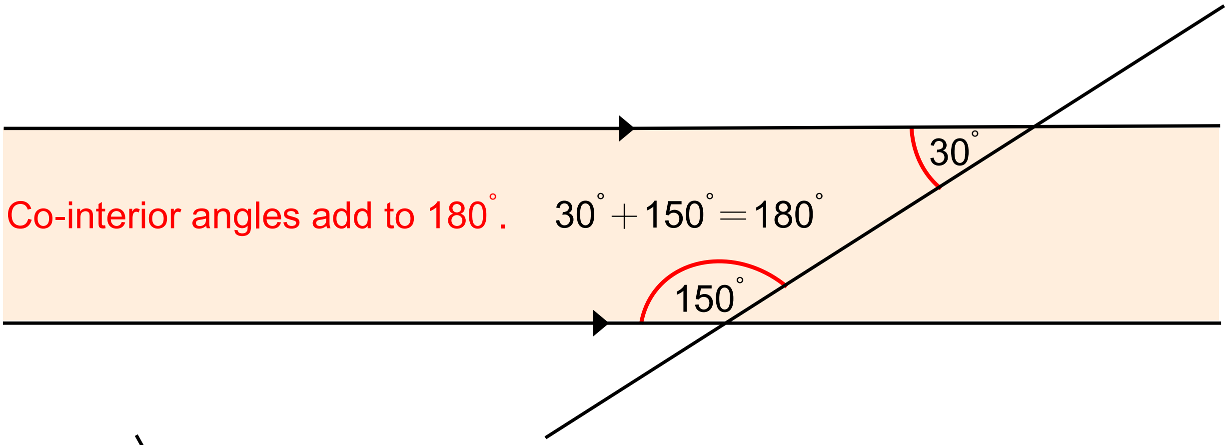


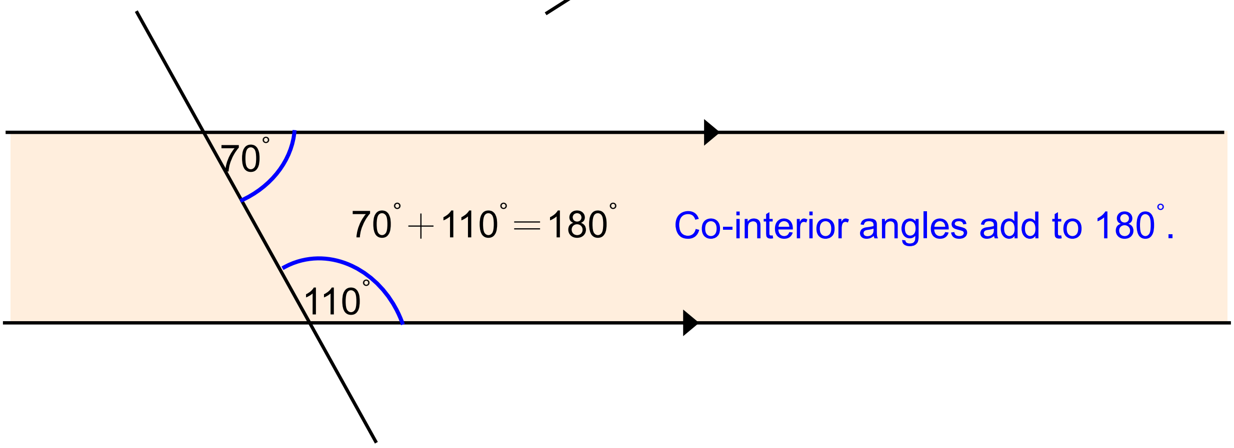
When parallel lines are crossed by a transversal, corresponding angles are equal, so x = 40.

Angle relationship 3:

Co-interior angles

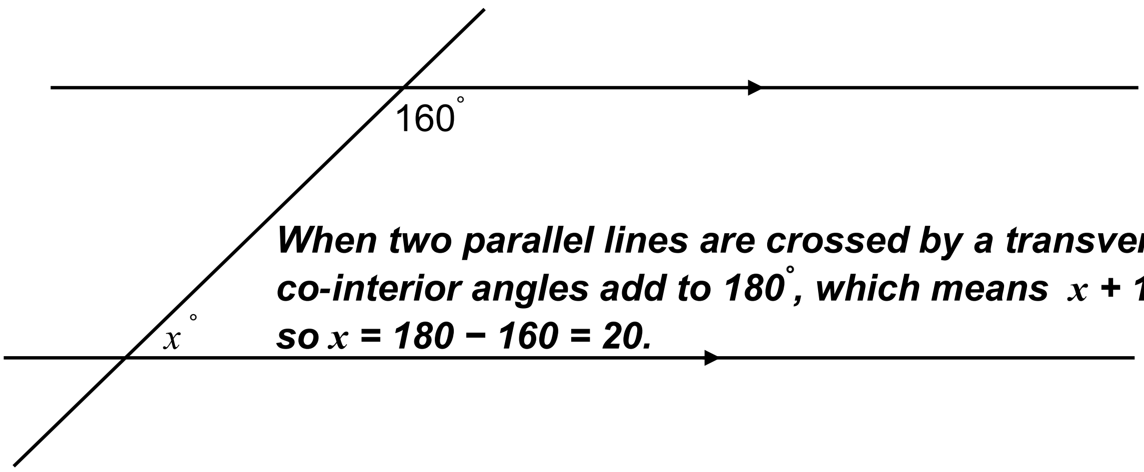
When two parallel lines are crossed by a transversal, the two angles <u>which are between the parallel lines and on the same side of the transversal</u> add to 180°.





How to use this relationship

Question: What is the value of x?



When two parallel lines are crossed by a transversal, co-interior angles add to 180°, which means $x + 160 = 180$, so $x = 180 - 160 = 20$.

Acquisition phase

[Instructions for the tracing on the paper group]

You will now be shown a worked example to study. Please use your index finger of your writing hand to help you learn. You will have 2 minutes to:

(1) Look at the worked example.

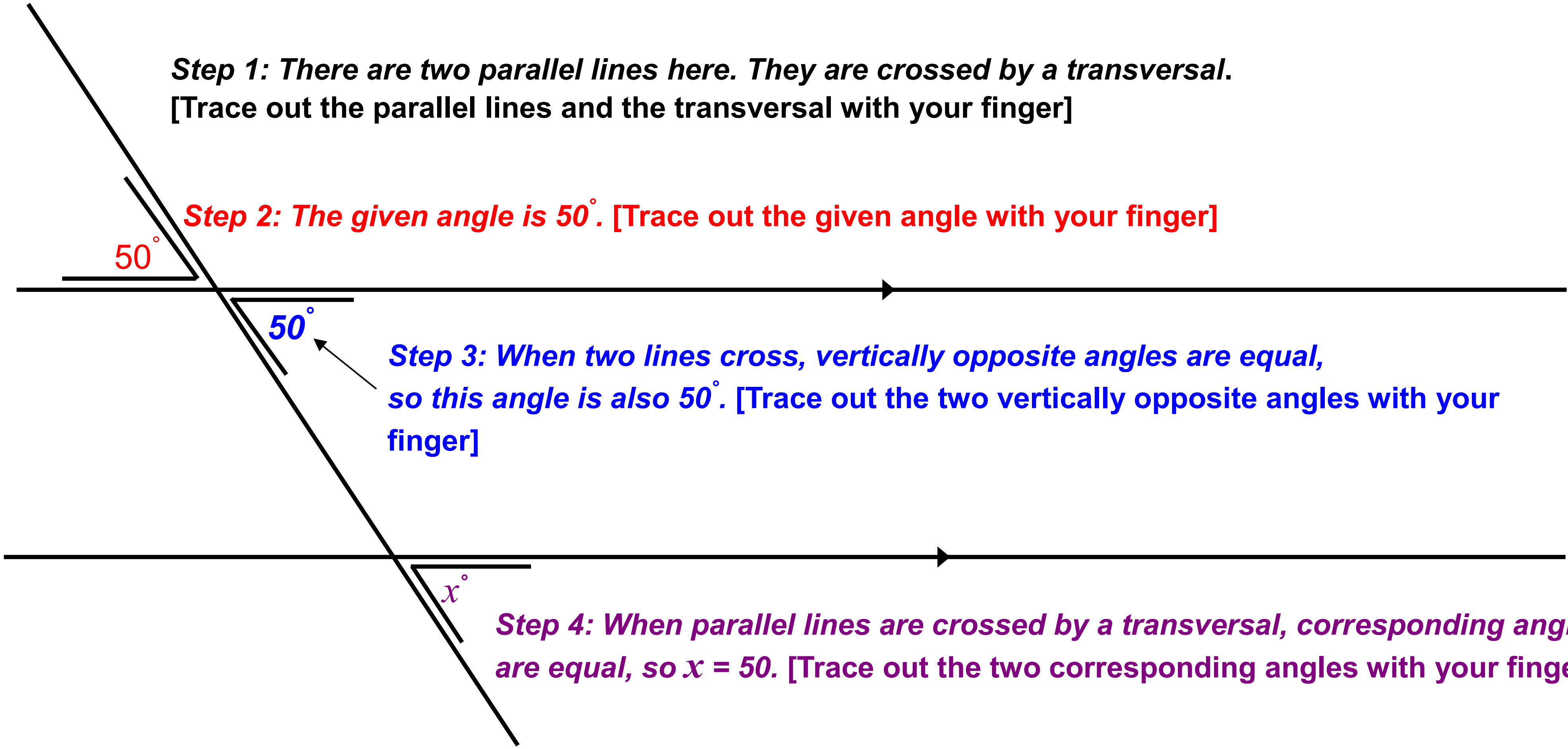
(2) Read the solution steps in the worked example carefully.

(3) As the instructions in brackets tell you, use your index finger to trace out the diagram on the paper.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

Worked example 1:

Question: What is the value of x?



***Step 1: There are two parallel lines here. They are crossed by a transversal*. [Trace out the parallel lines and the transversal with your finger]**

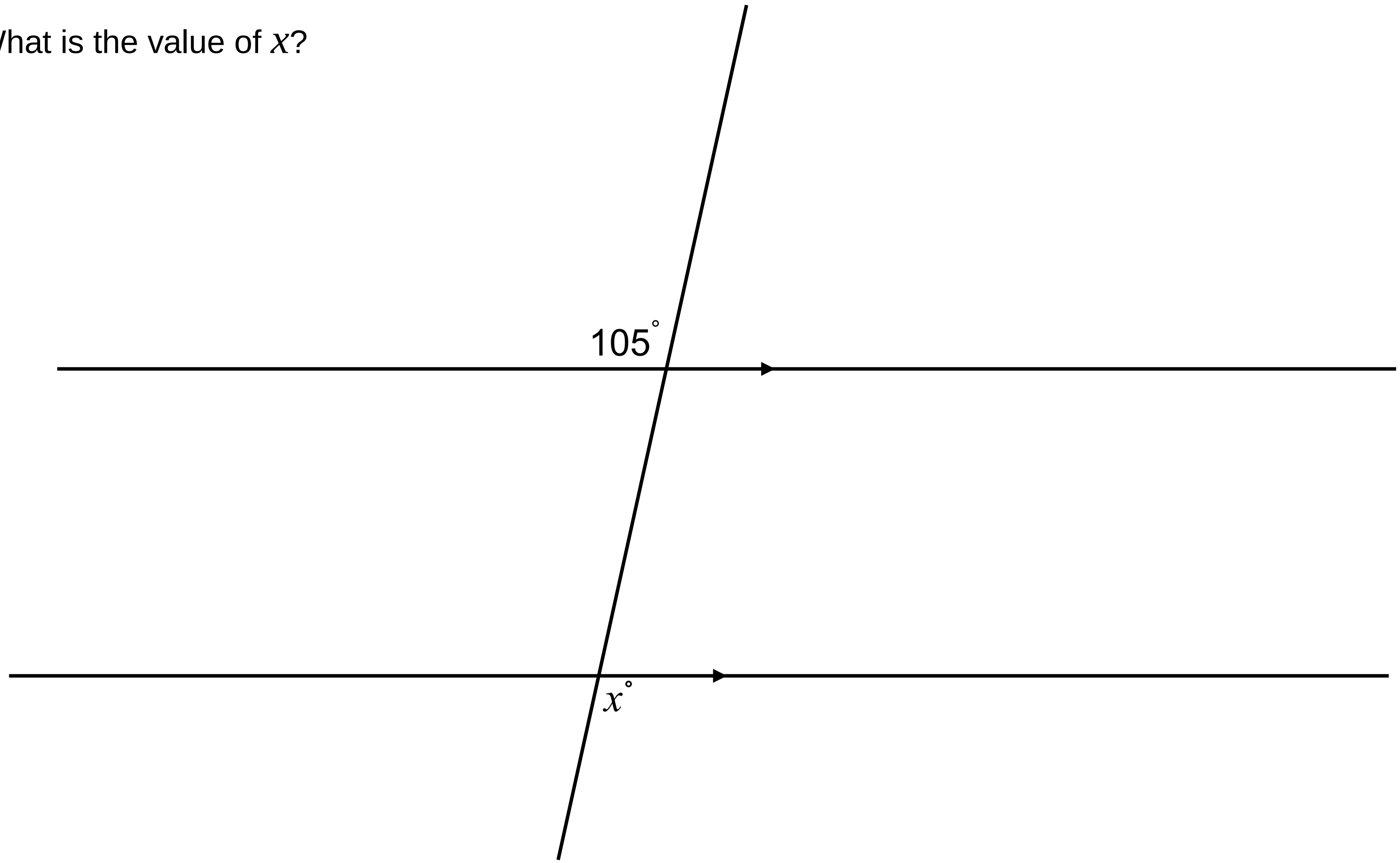
***Step 2: The given angle is 50°.* [Trace out the given angle with your finger]**

***Step 3: When two lines cross, vertically opposite angles are equal, so this angle is also 50°.* [Trace out the two vertically opposite angles with your finger]**

***Step 4: When parallel lines are crossed by a transversal, corresponding angles are equal, so x = 50.* [Trace out the two corresponding angles with your finger]**

Practice question 1:

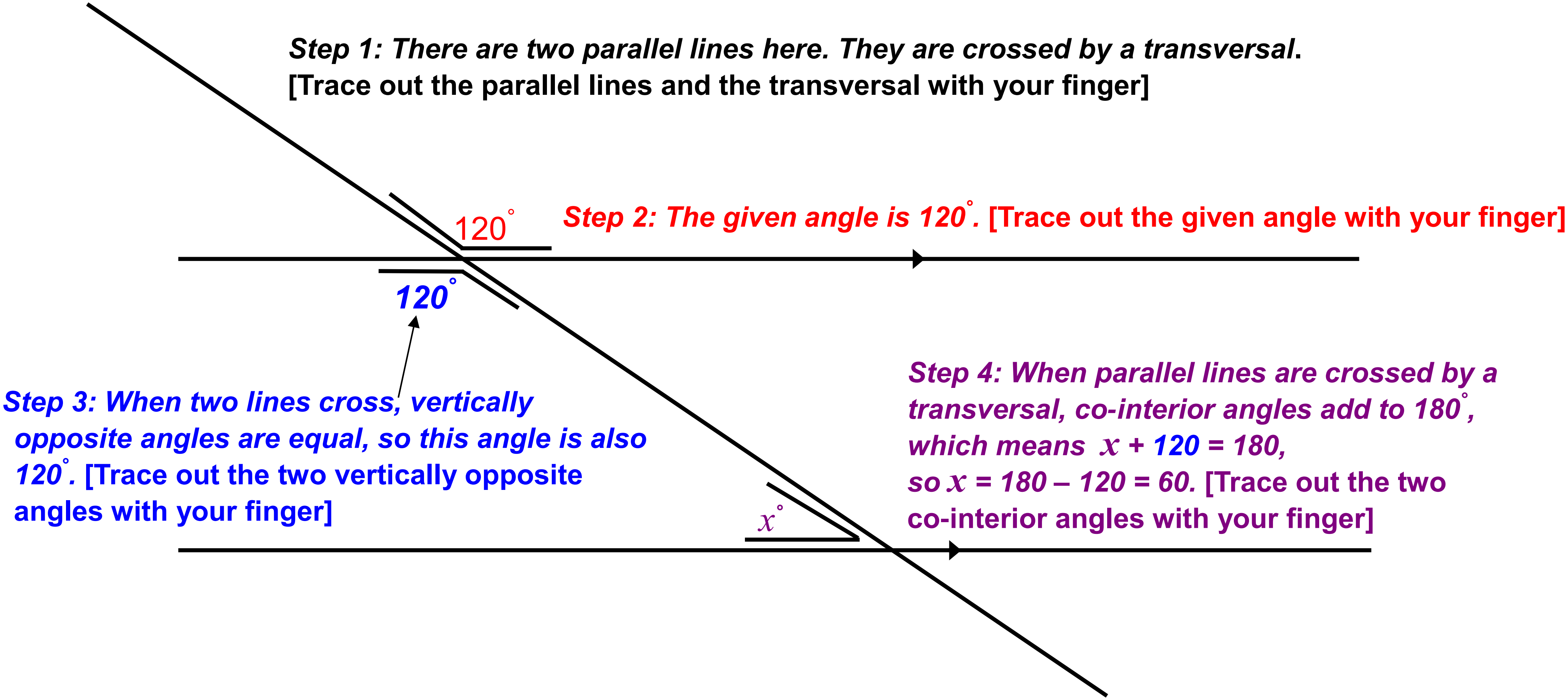
Question: What is the value of x?



Answer: x = __________

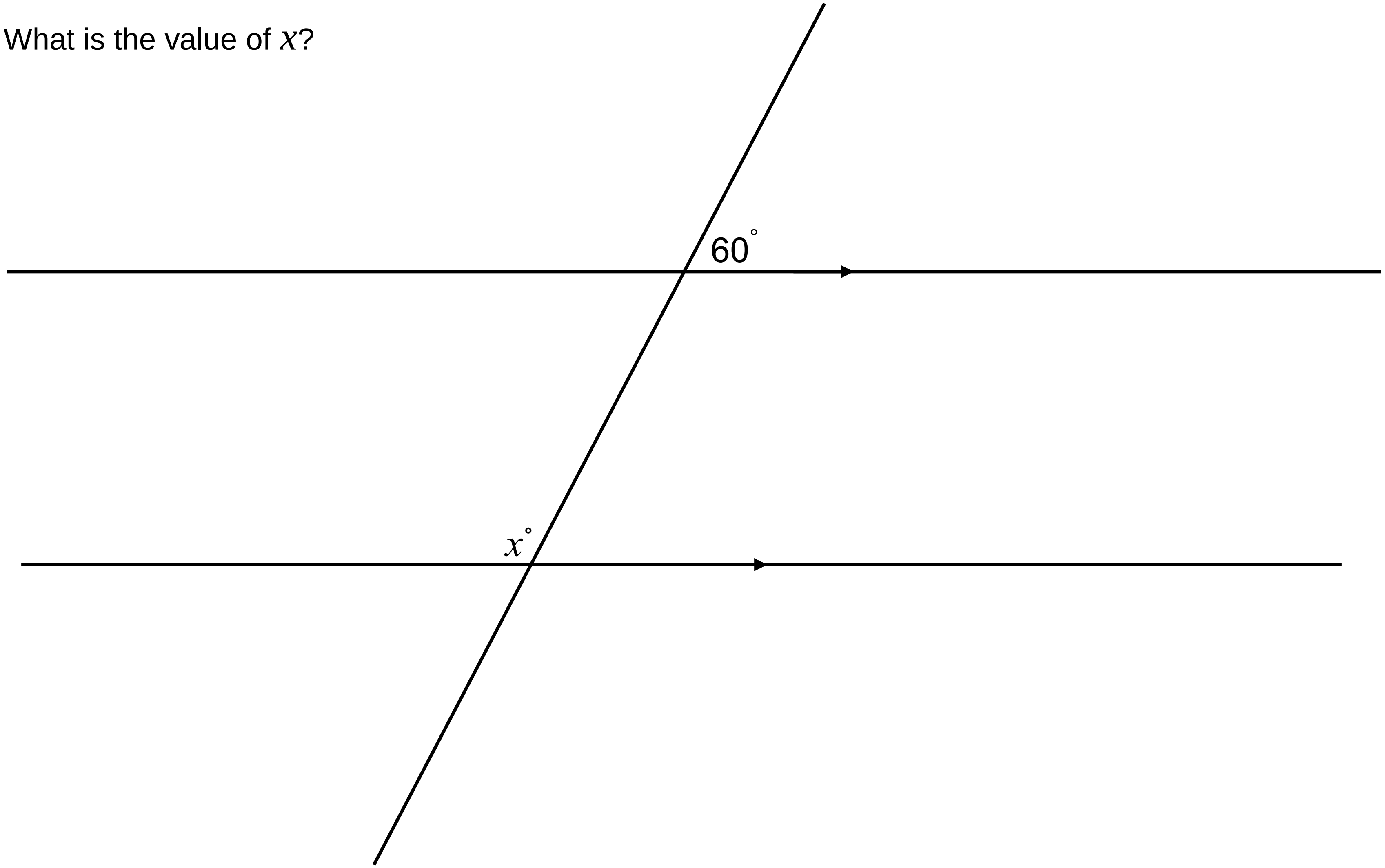
Worked example 2:

Question: What is the value of x?



Practice question 2:

Question: What is the value of x?



Answer: x = __________

Acquisition phase

[Instructions for the tracing in the air group]

You will now be shown a worked example to study. Please use your index finger of your writing hand to help you learn. You will have 2 minutes to:

(1) Look at the worked example.

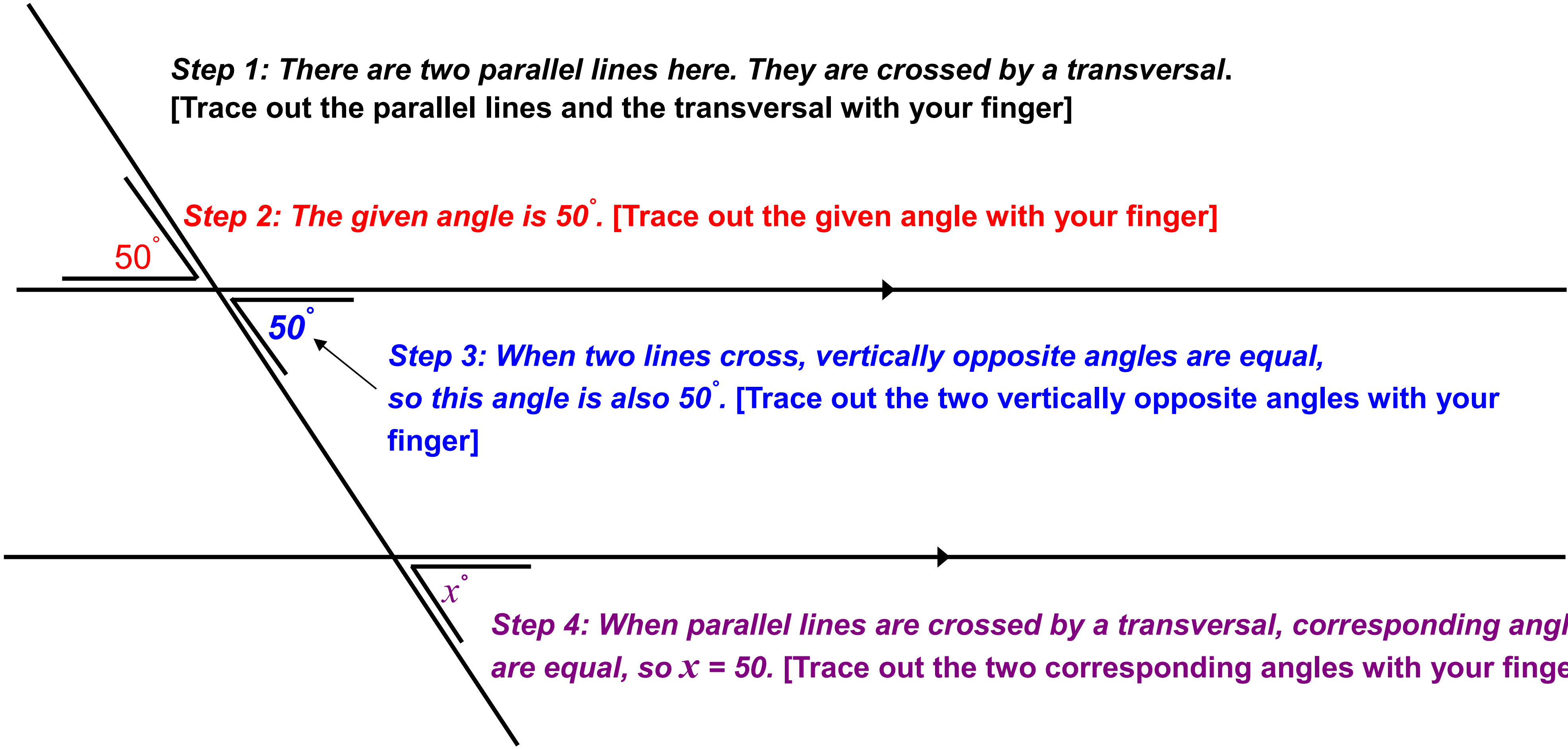
(2) Read the solution steps in the worked example carefully.

(3) As the instructions in brackets tell you, put your index finger above the paper about 5 cm and trace out the diagram without touching the paper.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

Worked example 1:

Question: What is the value of x?



***Step 1: There are two parallel lines here. They are crossed by a transversal*.**
[Trace out the parallel lines and the transversal with your finger]

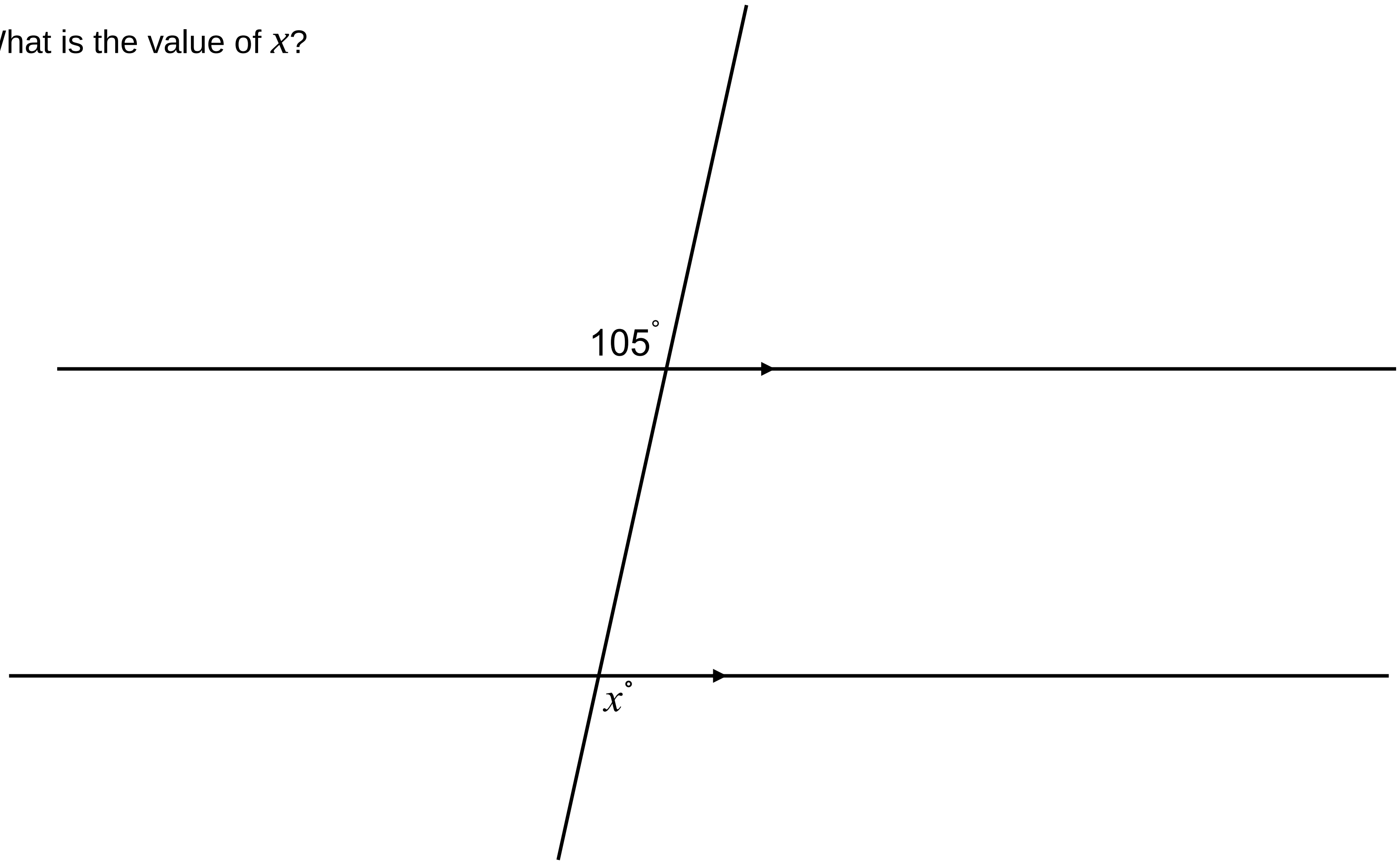
***Step 2: The given angle is 50°.* [Trace out the given angle with your finger]**

***Step 3: When two lines cross, vertically opposite angles are equal, so this angle is also 50°.* [Trace out the two vertically opposite angles with your finger]**

***Step 4: When parallel lines are crossed by a transversal, corresponding angles are equal, so x = 50.* [Trace out the two corresponding angles with your finger]**

Practice question 1:

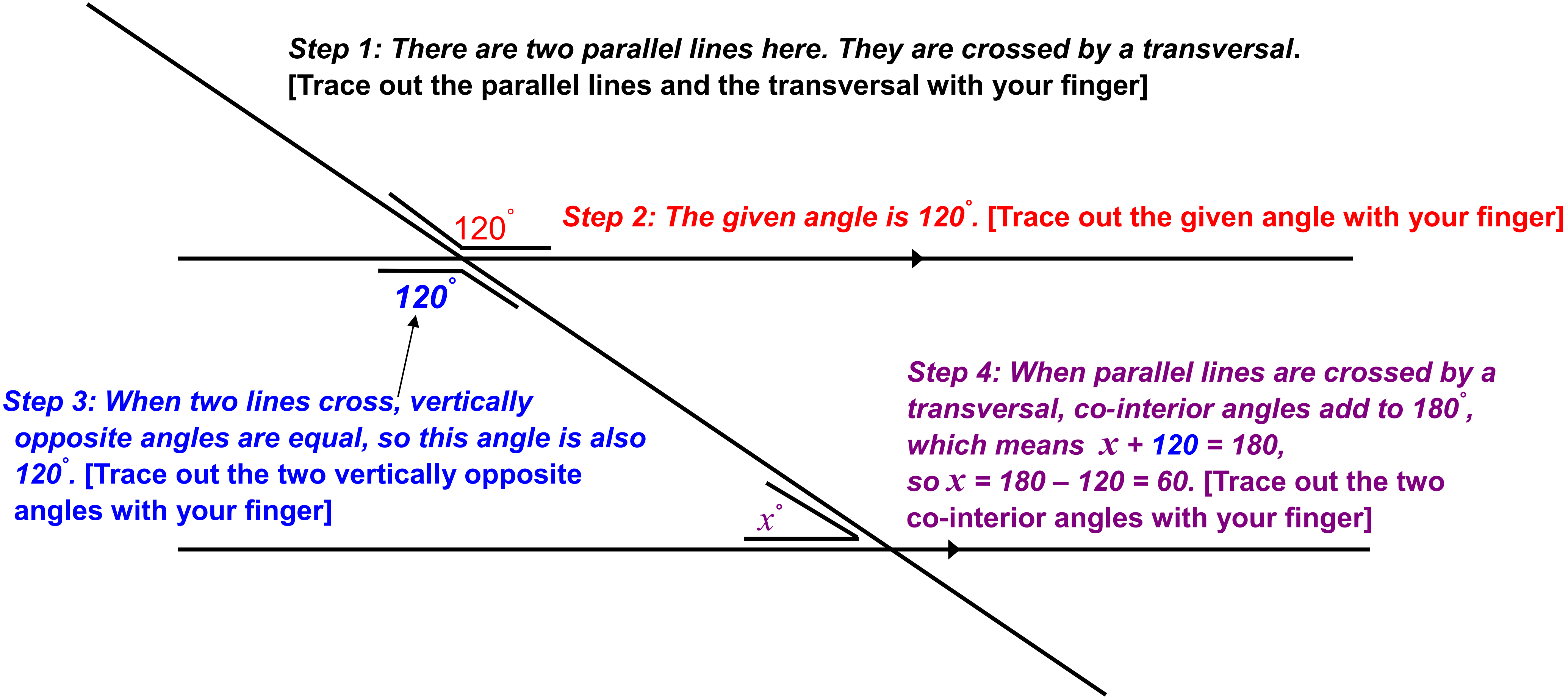
Question: What is the value of x?



Answer: x = __________

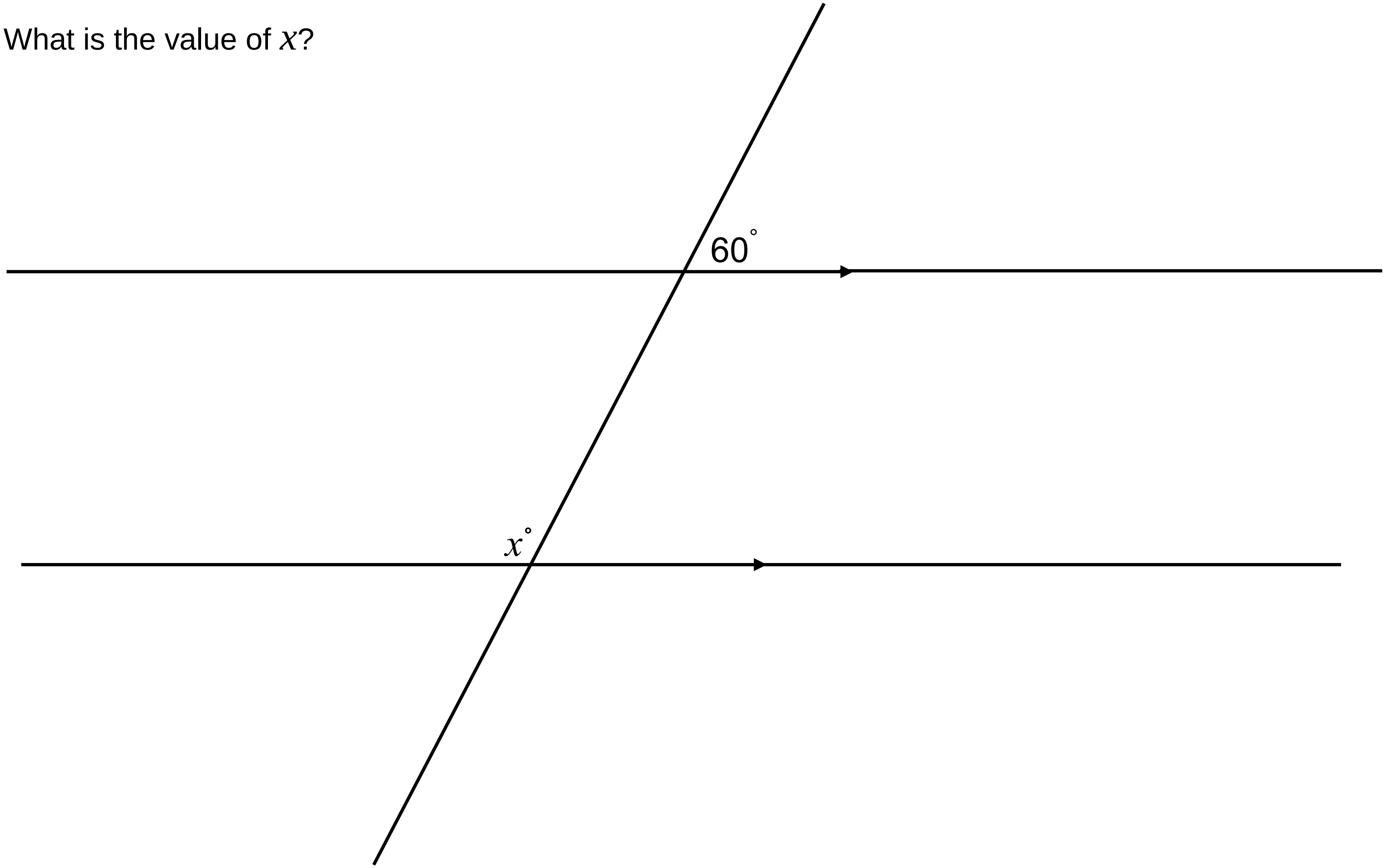
Worked example 2:

Question: What is the value of x?



Practice question 2:

Question: What is the value of x?



Answer: x = __________

Acquisition phase

[Instructions for the non-tracing group]

You will now be shown a worked example to study. Please put your hands on your lap.

You will have 2 minutes to:

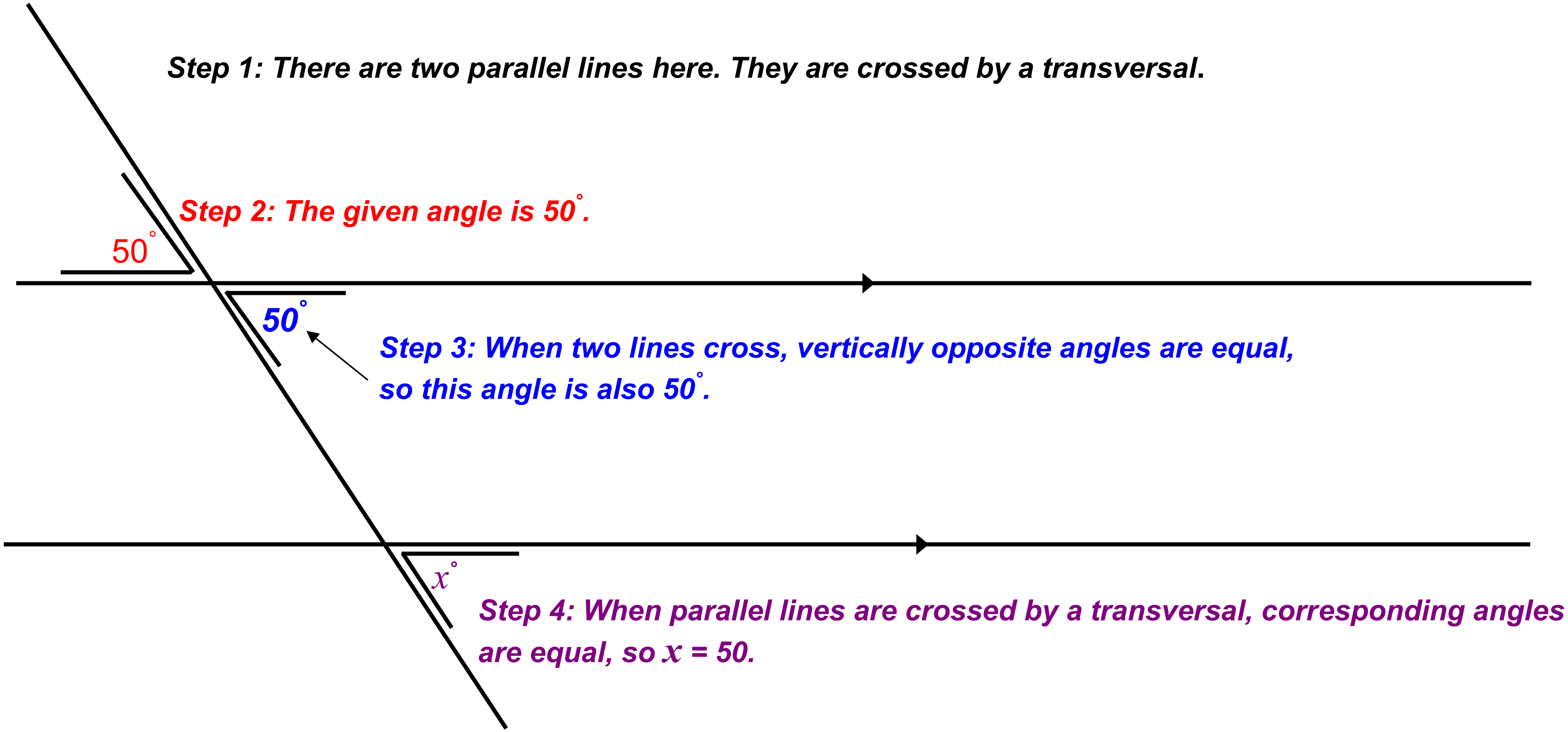
(1) Look at the worked example.

(2) Read the solution steps in the worked example carefully.

Please make sure you concentrate on this task because you will be given a very similar problem to solve immediately afterwards.

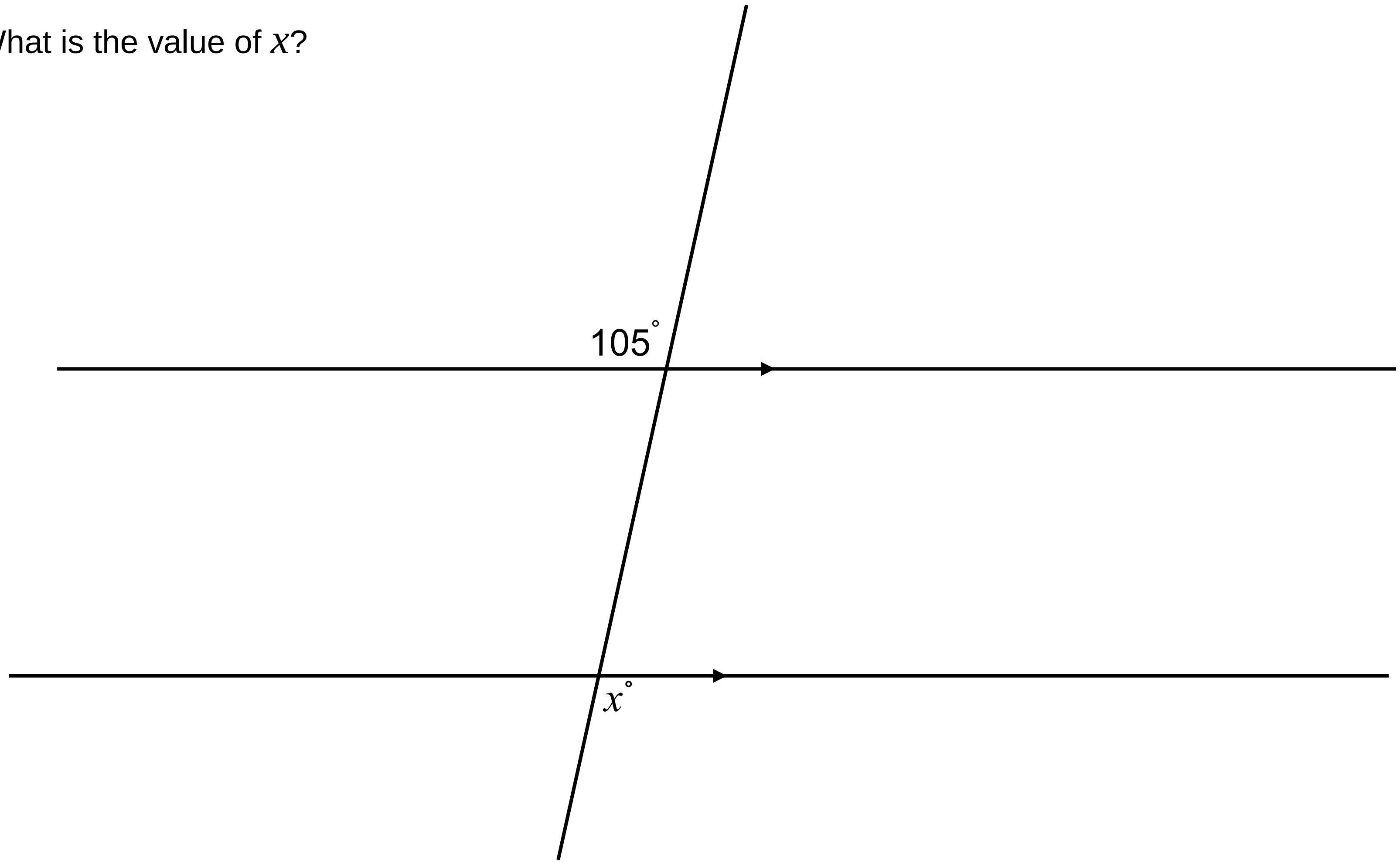
Worked example 1:

Question: What is the value of x?



Practice question 1:

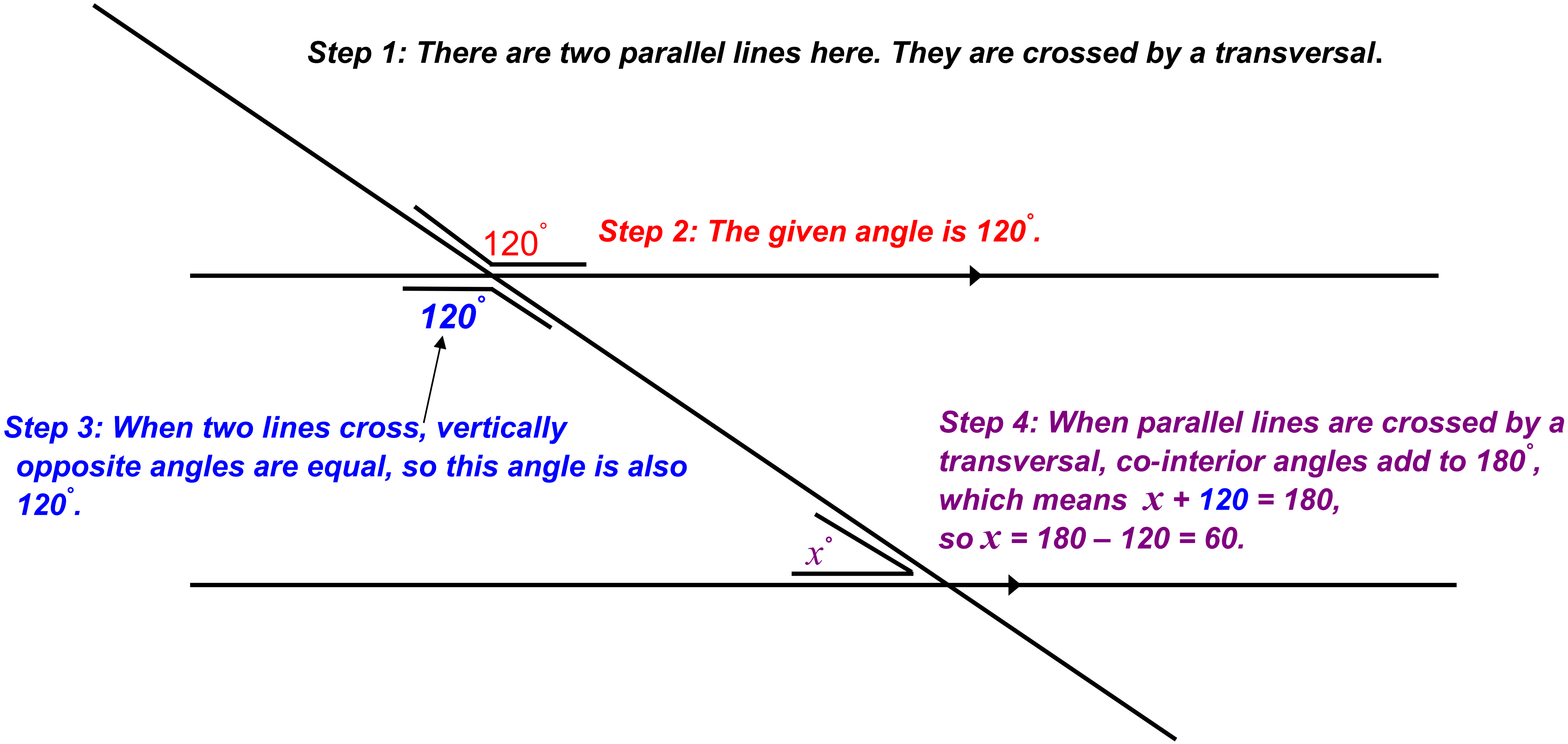
Question: What is the value of x?



Answer: x = __________

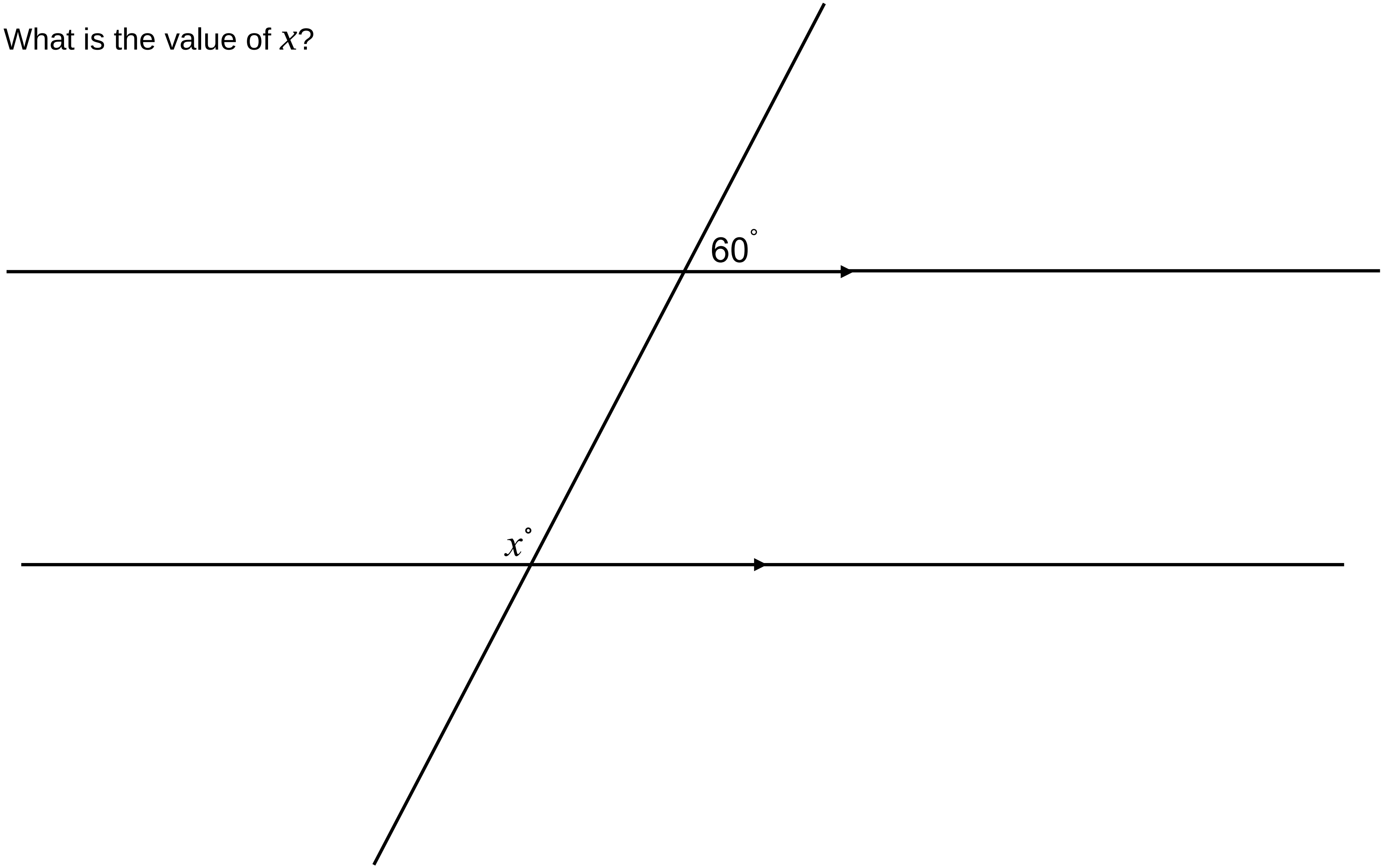
Worked example 2:

Question: What is the value of x?



Practice question 2:

Question: What is the value of x?



Answer: x = __________

Test phase

[Instructions for both groups]

You will now be given 8 problems to solve.

Please apply the angle relationships you have just learned to solve the problems and write down the working for each step to your solution on the diagrams.

You will have up to 60 seconds to solve each problem.

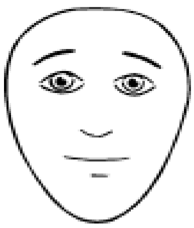
If you work out an incorrect answer, I will tell you and then you can continue trying to work out an answer.

If you have any questions about the test, please ask now.

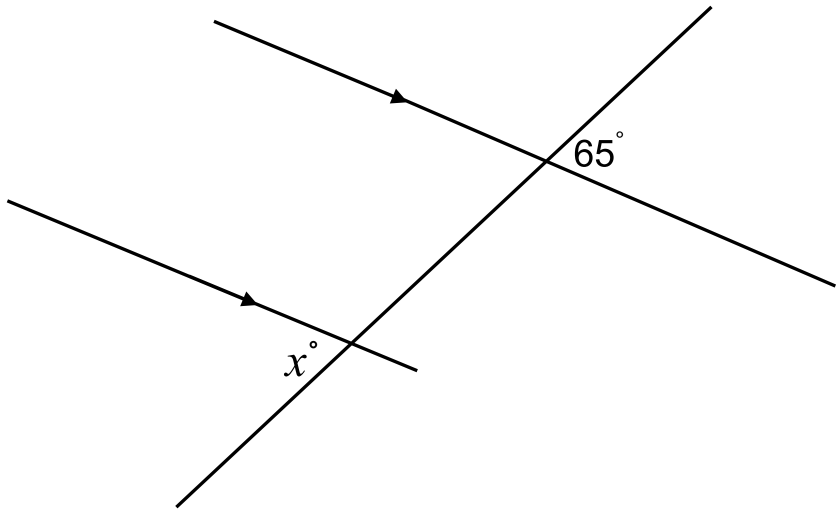
Cognitive Load Ratings (to be collected after each of the questions below)

[Instructions for both groups]

The faces show how people feel when trying to solve a problem. The left-most face shows people find it very easy to solve a problem. The right-most face shows people find it very difficult to solve a problem. After solving each problem, you will be asked how you felt about solving this problem. Please point out if you found the problem very easy, very difficult, or somewhere in the middle.

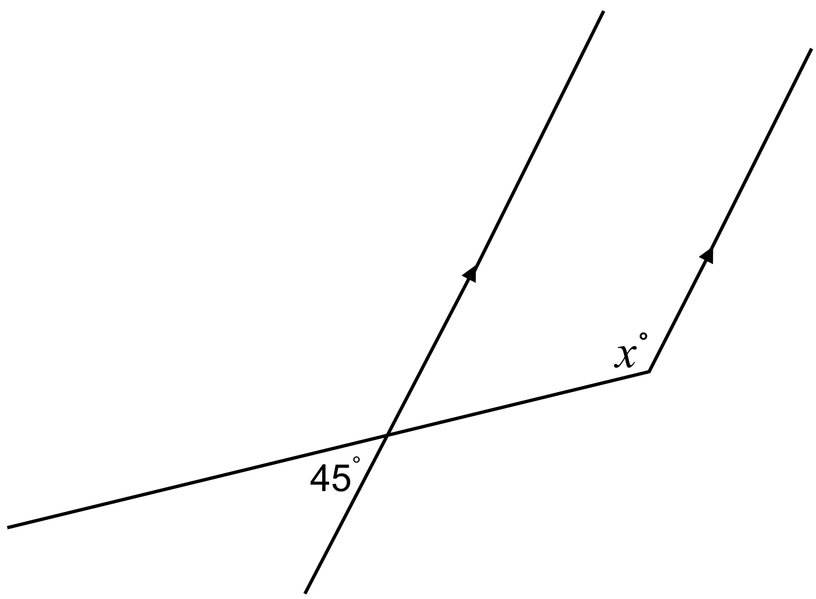
 Very easy				 Very difficult
1	2	3	4	5

Question 1: What is the value of x?



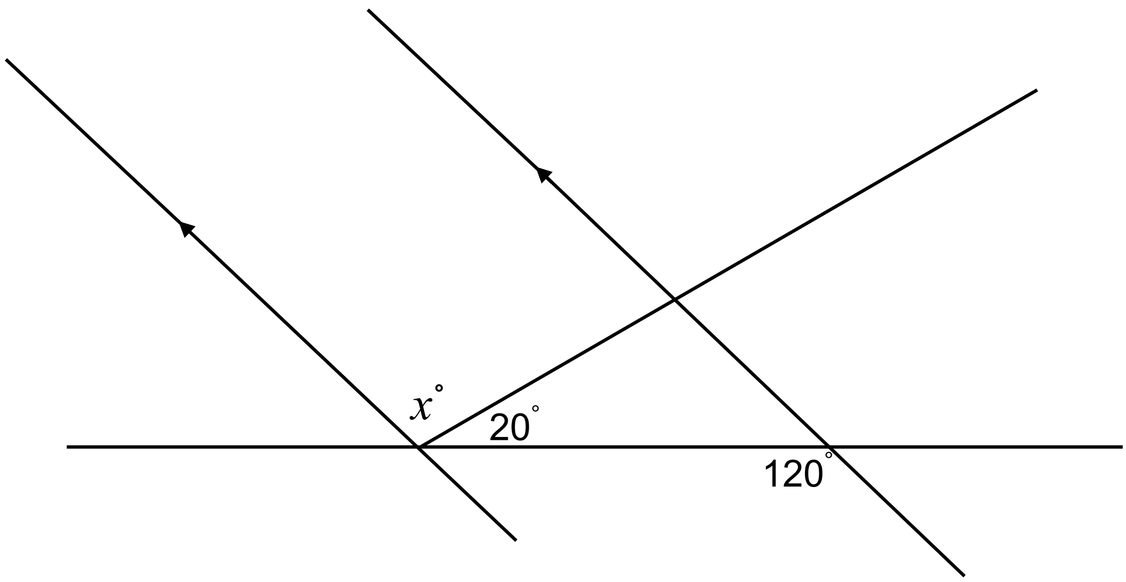
Answer: x = __________

Question 2: What is the value of x?



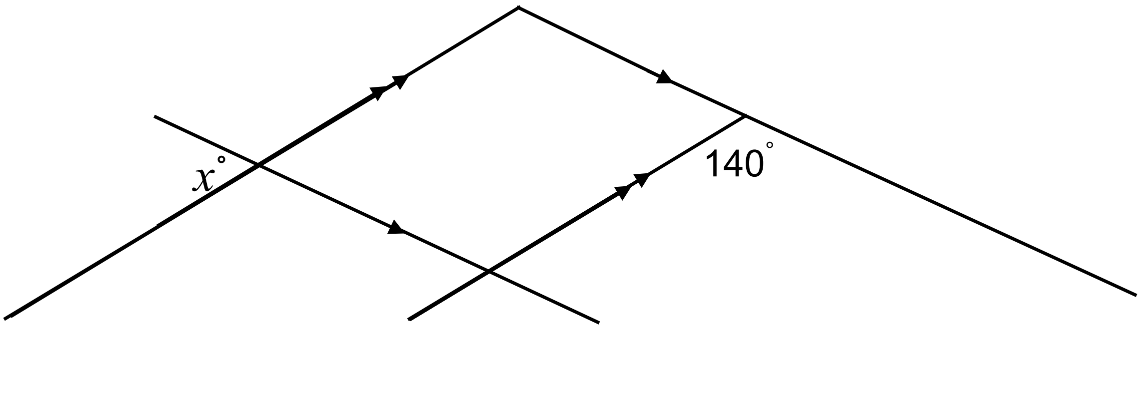
Answer: x = __________

Question 3: What is the value of x?



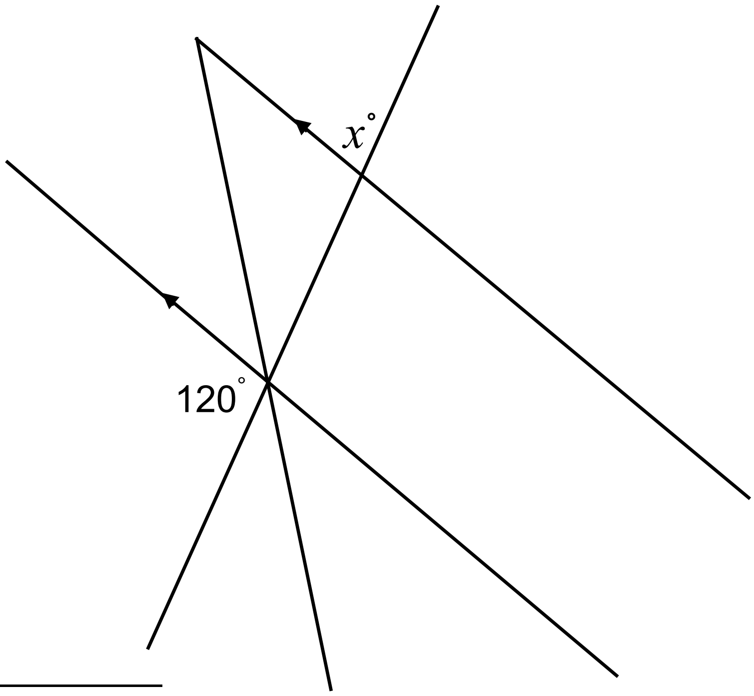
Answer: x = _________

Question 4: What is the value of x?



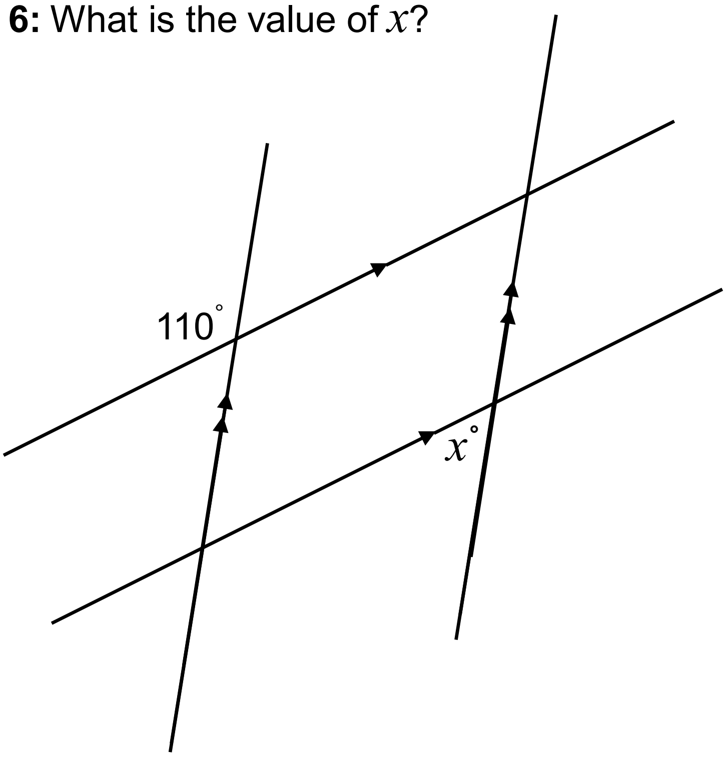
Answer: x = _________

Question 5: What is the value of x?



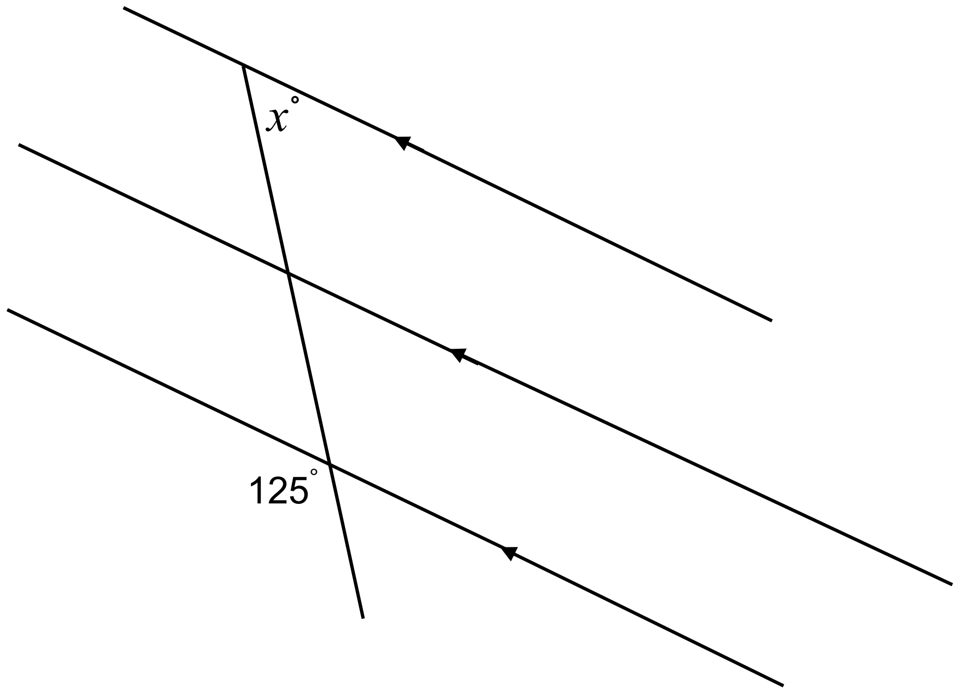
Answer: x = __________

Question 6: What is the value of x?



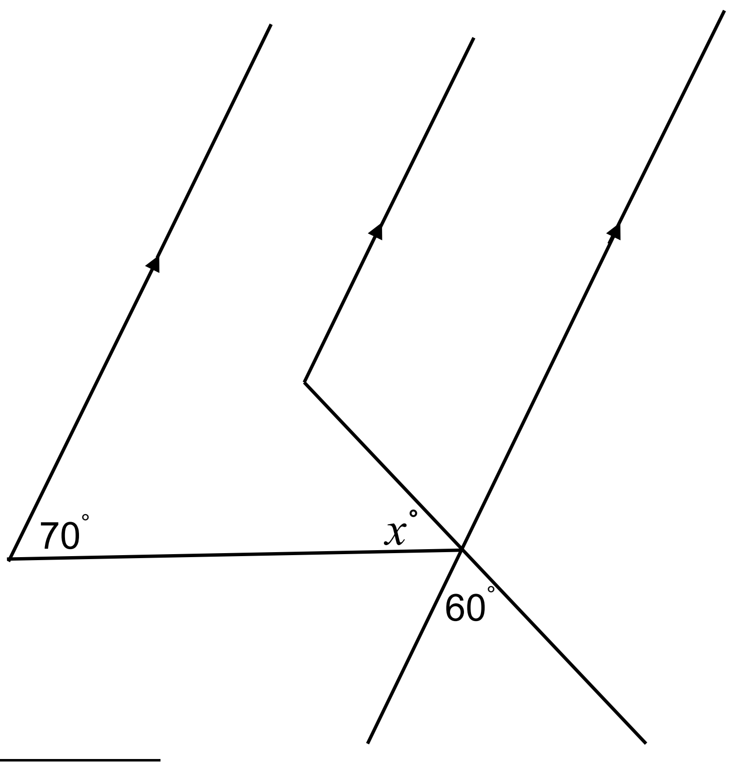
Answer: x = __________

Question 7: What is the value of x?



Answer: x = __________

Question 8: What is the value of x?



Answer: x = __________