Chapter 2
Review of Related Literature

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Chapter 2

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2.1 Introduction

The meaning ascribed to the term, buoyancy, is extremely diverse ranging from ‘force due to fluid pressure’ (Academic Press Dictionary of Science and Technology, 1992), ‘lifting effect of a fluid’ (The Hutchinson Dictionary of Science, 1998), ‘apparent loss in weight’ (Chambers Dictionary of Science and Technology, 1999), a ‘tendency’ (Mott, 1994) and even the ‘ability to float’ in lay terms (Longman Dictionary of contemporary English, 1995). However, generally, scientists and engineers use the term buoyancy synonymously with buoyant force. To avoid confusion, in this research, the force is referred to as ‘buoyant force’, and ‘buoyancy’, a domain which is depicted in Figure 2.1.

![Buoyancy domain](image)

This chapter mentions in brief, the entities of the buoyancy domain, highlights some misconceptions previously uncovered by science researchers, and critiques computer-based instructional and learning strategies that have been implemented for the domain. This is followed by a description of the four foundations of this research: psychological and pedagogical foundations, related computer-based learning environments, and relevant human-computer interaction issues.

2.2 Buoyancy Domain

2.2.1 Framework for buoyancy

Only the macroscopic level of the domain for liquid is explored, though buoyancy is essentially a fluid phenomenon. The entities of the domain as illustrated in Figure 2.1, are principles, forces, and observed phenomena.

2.2.2 Conception of buoyancy

Predominantly, conducted buoyancy-related researches aim to gain insights into children’s understanding of when and why an object floats or sinks (Biddulph, 1983; Halford et al., 1986;
Hewson, 1986). In these researches, subjects predicted whether a given object would float or sink supported by a justification. Their findings reveal that many children have gross misconceptions about floating and sinking phenomena and typically, their explanations are not grounded on the crucial concept of the relative densities of object and medium.

Biddulph and Osborne (1984) extended the ‘when and why’ understanding of floating and sinking phenomena to encompass children’s qualitative understanding of causal factors on a floating object. The two factors investigated were the causal effects of the length of a floating object, and depth of the medium on flotation. Evidently, the children demonstrated conflicting understanding of these causal relationships. Some thought the longer piece of object would sink because it is heavier and some were certain it would float higher because ‘more of it is held up by water’. As for the change in the depth of medium, some predicted a floating object would float lower in deeper water as it is ‘sucked’ down a bit while some surmised it would float higher because of more pressure beneath.

Su Gang (1993) conducted a one-to-one interview with children of about 14 years of age who had not received formal instruction on Archimedes’ Principle. Several misconceptions unveiled are: the larger the base area effects a bigger buoyant force; a hollow steel ball experiences a larger buoyant force than a solid ball because there is air in the hollow ball. Also, the consideration of the depth of submergence induced contradictory conceptions. Some children predicted that the exerted buoyant force decreases with an increase in the submerging depth while some thought otherwise.

In summary, the subjects for most reviewed buoyancy-related researches are children whose ceiling age is at the most 18 years of age. This calls for the need to investigate how subjects beyond this age group reason about the domain. The predictive rule of floating and sinking forms the crux of most researches and students’ causal understanding of the phenomena is underplayed. Our research aims to extend the notion of buoyancy-related understanding by incorporating more causal as well as non-causal factors that relate to the attributes of the object and the medium for both floating and sinking phenomena). All the factors already investigated by Biddulph and Osborne (1984) and Su Gang 1993) will be replicated. These factors are listed in Chapters 3 and 4.

2.2.3 Computer-based modelling for buoyancy

Frenette (1989) provides an interactive and exploratory learning environment for 6th and 7th graders. The central concern of such an exploration is to discover the predictive rule for floating
and sinking based on relative densities of materials which is hinged on essential prior conceptual understanding of density.

However, distinguishing density from mass is an uphill task for many children due to the fact that density is a ratio concept. Snir et al. (1995b) argue that before a student could use the density concept to explain and understand flotation phenomena, with emphasis on relative densities, he must first be able to grasp the distinction between mass and density. Consequently, Snir and his co-workers developed a conceptually enhanced simulation which allows students to perceive what cannot be directly observed in a normal physics laboratory. For example, the volume of an object is visually represented by rectangular tiles with standard size-units. As for mass, its visual iconic representation is a rectangular mass unit. The number of mass units in each volume tile visually depicts density (mass per unit volume). Such a visually represented abstract concept could be used to exemplify Teodoro’s (1994) notion of ‘concrete-abstract’ objects. These objects appear to be concrete on the computer screen because they can be manipulated. However, in reality, these ‘concrete-abstract’ objects are intangible physical constructs. He gave the example of the vector, velocity, which is depicted visually as an arrow that can be directly manipulated.

As highlighted earlier, most of the investigations conducted on children’s understanding of when and why objects float or sink, overemphasise relative density thus neglecting buoyant force. Consequently, Raghavan and Glaser (1994) developed a model-based buoyancy-related curriculum for middle school students. This curriculum focuses on the ‘when and why’ understanding of floating and sinking again, but with an emphasis on buoyant force which is actually the underlying mechanism that links density with this observable phenomena. This computer-based curriculum provides an interactive computer environment which permits students to inspect, predict, and manipulate the following variables: surface area, volume, density of liquid and object, mass, force, as well as pressure on an area. The model presents an object fully immersed in a liquid and addresses the quantitative aspect of downward force due to gravity, upward buoyant force and the net or resultant force. It allows students to predict the net force, observe the effects of the prediction on the object and compare it with what would happen in reality.

In conclusion, the computer-based buoyancy curricula and previously mentioned research are alike in their primary focus: the ‘when and why’ understanding of floating and sinking. This research endeavours to go beyond such a limited scope of investigation. As mentioned in the preceding section, the domain for the computer-based learning environments designed for the
purpose of this research encompass causal as well as non-causal factors so as to facilitate a more complete understanding of the domain.

Raghavan and Glaser (1994) introduced three forces in their model: force due to gravity, buoyant force, and net force. These terms are phrased in a formal language which students might find difficult to grasp. In addition, the term net force used is too general and vague. In order to address this issue, our final model replaces the usual formal terms with simple object-related terms (discussed further in Chapter 4). The familiar object-related terms selected are: Body Force, to replace force due to gravity; String Force (tension), to substitute for net force; and Liquid Force, to stand in for buoyant force. Their respective definitions are phrased in lay terms so as to make them more meaningful and the list of definitions can also be found in Chapter 4. Notably, the general and vague net force is represented by the reading of a spring balance in the prototype system, and tension in the final system, which students are more familiar with. The rationale for this is to facilitate their imagination and reasoning. In addition, the inclusion of a third object into the model, the spring balance or the string, causes the whole model to be in an equilibrium state, thus curbing the noise from hydrodynamics and limiting the domain to hydrostatics alone. Teodoro’s (1994) notion of ‘concrete-abstract’ objects is borrowed to visually depict the three forces in the conventional form of arrows which are manipulable.

2.3 Foundations of this Research
This research is built on four bases: psychological and pedagogical foundations, features of related computer-based learning environments, and relevant human-computer interaction issues.

2.3.1 Psychological foundation
i. Vygotskian approach to education

Language as a psychological tool
Sign systems, according to Vygotsky, embody language, literacy and mathematics (Moll, 1990). Vygotsky (1978) perceived a sign as a psychological tool when he drew the following analogy: ‘a sign acts as an instrument of psychological activity in a manner analogous to the role of a tool in labour’ (p. 52) despite having highlighted many dissimilarities between the two. However, to elaborate the analogy further, the latter is employed to change one’s environment while the former ‘alters the entire flow and structure of the mental function’ (Minick, 1987, p. 20).

Vygotsky (1986) analysed verbal thought, the most elementary unit being ‘word meaning’ where the ‘meaning of the word’ represents the amalgam of thought and language. From the psychological point of view, ‘the meaning of every word’ is a generalisation or concept (p. 212).
He argued that since generalisations and concepts are acts of thought so meaning is a phenomenon of thinking. To Vygotsky, rational thinking is one of the higher mental functions (Minick, 1987). Saljo (1995) emphasises that when the act of thinking occurs then this means that simultaneously, the psychological tools that originate in language are in operation. When this happens, the description or understanding of an object or phenomenon is facilitated. In other words, through language, we understand and describe the world, and also we could communicate our intentions to others.

**Vygotsky’s zone of proximal development concept**

Moll (1990) defines the term ‘zone’ as a social system where an individual is placed in a concrete social situation of learning and development. In the 1930s, Vygotsky introduced the concept of ‘zone of proximal development’ (ZPD) to cognitive development. ZPD relates to the development of a skill or ability with and without support. Here we illustrate the notion of ZPD in Figure 2.2. The level at which a person can perform a task independently is the actual level of development, and with help, he will be able to perform the task at a higher level, which is his potential level of development. Vygotsky’s notion of ZPD is the difference between these two levels (Hedegaard, 1990). This means that in this particular zone, an individual is directed toward his full development with ‘assistance’.

![Diagram of Zone of Proximal Development](image)

**Figure 2.2: Zone of proximal development**

Sewell (1990) explains that the dual purpose of such ‘assistance’ is to first expose the adequacies and inadequacies in the individual’s current levels of thinking, and to then proceed to a higher level of understanding. Valsiner (1988) suggests that ‘assistance’ here embodies socially provided resources for the process of a learner’s development. However, Vygotsky himself never specified the forms of social assistance to learners in the zone of proximal development (Moll, 1990). Vygotsky wrote about collaboration and direction, and about assisting learners for example through demonstration, leading questions but did not specify beyond those general
prescriptions. Based on his point of view, ‘assistance’, typically refers to direct interaction such as instruction, collaboration or tutoring.

**Vygotsky’s notion of scientific versus spontaneous concepts**

Vygotsky (Rieber & Carton, 1987) stated that knowledge is transferred to a learner in a definite system. What is this definite system? It is referred to as the social organisation of instruction (Moll, 1990). Development is a phenomenon that occurs as part of the educational process with systematic co-operation between a teacher and a learner, and a learner’s higher mental functions mature during this process. Such maturation lies in the zone of proximal development. As shown in Figure 2.3, the development of scientific concepts first begins with verbal definitions which tends to descend to the concrete that is the phenomena the concept represents. On the contrary, everyday concepts develop outside any definite system, and tend to move upwards toward abstraction and generalisation.

![Diagram](image)

**Figure 2.3:** ‘Descend’ and ‘ascend’ processes of scientific and spontaneous concepts

Differences between scientific concepts and spontaneous concepts suggested by Vygotsky are that they have a different relationship to the learner’s experience, a different relationship to the objects they represent (Rieber & Carton, 1987). Firstly, spontaneous concepts are experienced outside the school environment and the learner has immediate relationship with the objects they represent. Conversely, scientific concepts are experienced by the learner in a school, and the learner encounters the object or set of objects mentioned in the concept through a mediated relationship, that is a set of verbalisms. Vygotsky (1986) pointed out that it is this set of verbalisms that explains why a scientific concept is difficult, excessively abstract, detached from reality, and insufficiently saturated with the concrete. Vygotsky (1986) also compared the difficulty in defining a scientific and spontaneous concept. He argued that the definition of the former is complex but easier to formulate because of the teacher’s explanation in class. Although
spontaneous concepts (for example, the word ‘brother’) saturate a learner’s experience their definition is extremely difficult to formulate. We call this the ‘language deficiency syndrome’.

Moll (1990) wrote that Vygotsky emphasised that both types of concepts are interconnected and interdependent. Through everyday concepts, children make sense of definitions and explanations of scientific concepts. They mediate the acquisition of scientific concepts. Scientific concepts grow down into the everyday domain of personal experience, acquiring meaning and significance and in so doing, everyday concepts develop upwards to the scientific. West and Pines (1985) use the metaphor of a vine to denote the two processes depicted in Figure 2.3. The upward growing vine originates from a learner’s intuitive knowledge of the world, while the downward growing vine originates from formal instruction. According to them, genuine conceptual learning involves the two vines intertwined together. Vygotsky did not elaborate the ‘descend’ and ‘ascend’ processes depicted in Figure 2.3. Naturally, we raise the question of how to integrate these two processes. An excellent example is Kolb’s cycle of experiential learning (Kolb and Fry, 1975) which is illustrated in Figure 2.4.

![Figure 2.4: Slightly modified Kolb’s experiential learning cycle](image)

Concrete experiences form the basis for observation, reflection and reasoning and the outcome of these actions is an acquired abstract conceptual knowledge. When such knowledge is experimented with, it expands a learner’s repertoire of concrete experiences.

### ii. Piaget’s stage-independent theory of cognitive development

The essential elements of this theory addressed here are: schema, assimilation, accommodation, and equilibrium. Schemata, according to Piaget, are internal mental structures which depict the
way a person represents the world (Mayer, 1991), through perception, understanding and thoughts (Hill, 1990). When a piece of information is similar but not identical to a learner’s inherent knowledge structure, it will be assimilated by the existing cognitive structure. During this assimilation process, two changes will take place simultaneously. The first pertains to the stimulus itself while the second is the schema. The stimulus will be modified and, at the same time, the schema changes to accommodate the new input. The various ways of accommodating a new experience as outlined by Papert (1980) are abandoning the old or new knowledge, modify one or the other, or place both in separate mental compartments. When the conflict between the contradictory old and new knowledge has been resolved then equilibrium is said to have occurred. The schemata, in such a situation, are found to be in a stable state. Mendelsohn (1996) maintains that the notion of conflict is used as a tool, in the pedagogical field, to foster a conceptual change. The counter-examples used in Socratic Dialogue for a system called WHY (Stevens & Collins, 1977) is an example of how to incorporate such a notion of conflict in a computer system.

The above discussion pertains to information that is similar but not identical to the existing mental structure. The question that arises is what if the information is exactly the same or different altogether? According to Piaget (Mayer, 1991), neither has an influence on the schema because the former is nothing new while the latter can neither be understood nor encoded, thus cannot be related to the existing knowledge framework at all.

iii. Implications for this research

Vygotsky viewed language as a psychological tool to understand one’s environment. Thus, for the purpose of this research, a simple-object related language phrased in lay terms is provided for easy comprehension and also to enable students to relate to relevant prior knowledge, as well as to express their thoughts verbally. The environments provided in this research are interactive and are grounded on the ZPD concept in fostering a better understanding of the domain. The type of exploration afforded by the systems aims to support the upward growing vine so that students could abstract and generalise from their concrete experiences through observation, reasoning and reflection. This upward vine metaphor is closely related to the pivotal role of prior knowledge in Piaget’s notion of assimilation and accommodation. Thus novel situations with familiar objects are designed to utilise prior knowledge for the purpose of extending students’ knowledge structures.
2.3.2 Pedagogical foundation

i. Learning theory: Constructivism

The only theory discussed in this section is the constructivist theory of learning. In Bruner’s (1974) constructivist theory of learning, learning is viewed as an active process in which learners construct new ideas or concepts based on current or past knowledge. The three characteristics of constructivist learning portrayed here are: active, constructive and cumulative. Next, we elaborate on these three relevant properties of a constructivist learning process from Shuell’s (1992) cognitive point of view:

Learning is active

Shuell (1992) maintains that a learner must carry out various cognitive operations on newly encountered information in order for it to be acquired in a meaningful manner. However, he does not elaborate on the notion of the cognitive operations. Probably, the two subsequent characteristics to be discussed could help shed some light on them.

Learning is constructive

Here knowledge is not transferred to a learner but instead the learner builds a representation of the domain. According to Shuell (1992), every learner’s own constructed knowledge is somewhat idiosyncratic due to the fact that new information is perceived and interpreted based on the learner’s prior knowledge (Strike & Posner, 1985; Vosniadou & Brewer, 1992). Thus, learners create their own meaning of their experiences.

Learning is cumulative

Dewey (1902) stressed that it is imperative for students’ knowledge to grow from experiences and Ausubel (1968) maintains that what the learner already knows influences learning. The ideas of ‘growth’ and ‘influence’ are combined together when Shuell (1992) views learning as new knowledge being built on and influenced by learner’s prior knowledge. Prior knowledge here can either facilitate or inhibit learning in the case of misconceptions. This means prior knowledge is the crucial determining factor of the learning process and outcome (Ausubel, 1968; Duit, 1999).

Several constructivists put the knowledge construction process before the product or performance itself (Bettencourt, 1993; Jonassen, 1992a; von Glasersfeld, 1993). What does this learning process incur? Jonassen (1992b) refers to more general elements such as relating information to prior knowledge, interpreting new information in the light of prior knowledge, reorganising prior knowledge on the basis of newly acquired knowledge.
Implications of constructivism for the design of computer-based learning environments

Some of the implications of the constructivist perspective of learning are:

**Provision of novel situations**

Von Glasersfeld (1993) suggests that learners be given novel problems without any standard solution so that it will give us insight into how far they are on the way towards a workable conceptual network.

**Provision of rich environments**

Rich environments ought to support multiple perspectives, context-rich as well as experience-based activities (Jonassen, 1992a).

**Provision of cognitive learning tools**

Cognitive learning tools are tools designed for active learning so as to assist learners to represent their own knowledge or alternative representation of the external worlds (Kommers, Jonassen & Mayes, 1992).

**Emphasis on exploration**

Knowledge construction is made possible when an individual interacts naturally with his environment (Rieber, 1993) through unfettered exploration. However, it is imperative that learners be informed of the goals for an exploration.

**Focus on the evaluation of learning process**

Evaluation of learning should focus on the process of learning rather than the product (Akhras & Self, 1996).

ii. Views of learning

**Learning and understanding**

Generally, meaningful learning emphasises understanding more than behavioural change or performance (Shuell, 1992). However, defining ‘understanding’ is very difficult. Let us examine a classic notion of understanding put forth by Dewey (1933). Dewey first distinguished ‘information’ from ‘knowledge’ by arguing that ‘information is only knowledge as its material is comprehended’ (p. 78). In other words, ‘understanding’, here, is viewed as the bridge between information and knowledge. What then is ‘understanding’ from Dewey’s point of view? He explained that ‘understanding’ means that ‘the various parts of the information acquired are grasped in their relations to one another, a result that is attained only when acquisition is accompanied by constant reflection upon the meaning of what is studied’ (pp. 78-79). This implies that understanding of a piece of information is said to be attained when one is able to grasp a coherent network of its components with reflection being instrumental in this process. We attempt to illustrate Dewey’s notion of ‘understanding’ in Figure 2.5.
Shuell’s notion of ‘understanding’ is in line with that of Dewey’s when he maintains that the relationships among the concepts and facts are an integral part of understanding. He cites some of the characteristics associated with the concept ‘understanding’: paraphrasing, summarising, and answering questions. However, Scardamalia and Bereiter (1991) adopt Piaget’s assimilation and accommodation perspective of understanding when they posit that understanding is a two-way interaction between prior knowledge and new material. Here, prior knowledge interprets new material and on the other hand, new material modifies prior knowledge.

Ohlsson (1996) differentiates ‘learning to do’ from ‘learning to understand’. He stresses that the former concerns skill acquisition while the latter focuses on higher-order learning which relates to abstract knowledge. He cites some examples of the subordinates of higher-order knowledge: concepts, ideas, principles, and theories. He suggests that epistemic activities such as arguing, describing, explaining, predicting, etc are more relevant for higher-order learning. He maintains there is a close link between abstract knowledge and understanding. The question he raises is ‘What are the tasks that exercise understanding?’ (p. 49), which Shuell (1992) labels as ‘characteristics of understanding’. Ohlsson proceeds to advocate that success in performance does not imply understanding. On the other hand, failure does not imply lack of understanding. He creates a list of epistemic tasks to characterise ‘understanding’: describing, explaining, predicting, arguing, critiquing, explicating, and defining (p. 51). However, here, the point of contention is the possibility of solving epistemic tasks without understanding. He highlights the possibility of mastering the argument patterns to a level when they become so spontaneous that one can find an argument for or against any position effortlessly. However, novel and complex situations which incorporate these tasks, the ‘practice makes perfect’ effects could be nullified.

The next issue to be addressed here is how to model understanding. Kayser et al. (1999) use the term understanding to characterise ‘individual’s mastery of a complex web of interrelated facts and relationships, and their ability to use them to explain and predict phenomena’ (p. 1). Seemingly, this appears to combine Dewey’s outcome of the ‘understanding’ process and two of Ohlsson’s listed epistemic tasks for ‘understanding’. According to Kayser et al., learning is said to have taken place when there is a change in understanding in the form of some kind of change in the existing conceptual structure.

Figure 2.5: A schematic outline for the process of understanding
Learning and problem solving
Vosniadou (1995) states that learning to solve problems entails the acquisition of certain strategies and algorithms which make it possible to devise and execute a solution plan. Different groups of people analyse the problem solving process for different reasons. Firstly, a cognitive scientist focuses on the mechanisms underlying human reasoning, and the causes of errors. The educational scientist is concerned about the effect of education or the difficulties that pupils experience when solving problems. As for the knowledge engineer, he attempts to understand how a person executes a problem-solving task in order to create a computer system that can do the same. Next, we discuss very briefly, the two broad categories of problems: well-defined and ill-defined problems.

Well-defined problems
Well-defined problems are defined by four parameters: an initial state, goal state, set of operators, and path constraints (Newell & Simon, 1972; Greeno, 1976) with clearly specified solution steps. General Problem Solver (GPS) is a classic program developed for solving well-defined problems. It operates on problems that can be formulated in terms of objects and operators (Newell & Simon, 1972). VanLehn (1999) remarks that some basic concepts in GPS such as goals, subgoals, and operations have come to define a paradigm for understanding human problem solving.

Well-defined problems such as the ‘cannibal and missionary problem’ require little or no prior knowledge but hinge mainly on reasoning. Here, general problem solving strategies could be used to enable the problem solver to traverse from the original to the final goal state. Problem-solving is seen as a search through a state space. The essential characteristics of a problem space are: an initial state of knowledge; a set of operators which can be used at any point to generate a neighbouring point (intermediate states); an end state of knowledge (Newell & Simon, 1972).

A general strategy for this category of problem is means-ends analysis (Newell & Simon, 1972) which entails identifying the difference between the two states, and selecting the best action to reduce the difference. This is suitable for knowledge-lean domains. However, for knowledge-rich domains such as physics, prior knowledge is essential, and expertise involves acquiring a good repertoire of domain relevant knowledge as well as developing domain-specific problem-solving strategies (Vosniadou, 1995).
Ill-defined problems
With ill-defined problems, little or no information is provided on the initial state, goal state, or operators (Kahney, 1993). The problem has to be defined by the solver himself. Greeno (1976) argues that some problems with goals which are vague, undefined or limitless can be regarded as quite well-defined as long as solvers can find a solution path out of the many possible ones and work towards achieving the specified goal.

Learning and conceptual change
Strike and Posner (1985) explain how the conceptual change theory affects the general view of learning. According to them, conceptual change theory gives due emphasis to prior knowledge in learning and it also focuses on the transformation of conceptions in the learning process. They adopt the words, ‘accommodation’ and ‘assimilation’ from Piaget’s theory of equilibration to denote conceptual change. The former represents large-scale conceptual change while the latter refers to conceptual change of a lesser scale.


Schema change
Rumelhart et al. (1988) refer to a cluster of related concepts as a schema. They liken a schema as a kind of tree structure in which subschemata correspond to subtrees. Rumelhart and Norman (1977) classify three types of learning that can occur within a schema framework:

Accretion
Accretion occurs within existing schemata through the gradual addition of factual information interpreted in terms of relevant pre-existing schemata.

Tuning
Tuning involves the slow modification and refinement of schemata through continual use and, presumably, it is instrumental for the development of expertise.

Structuring
Structuring involves the creation of new schemata to account for new information.

Theory change
Vosniadou (1995) maintains that a theory structure differs from schemata in that it provides a causal explanatory framework within which a phenomenon it describes can be understood. In domain-specific theory change, Carey (1985) proposes a few possible changes: change in the
individual concepts that make up the theory, change in the relationships between the concepts, and change in the scope of the phenomena that the theory explains. Vosniadou’s (1995) notion of theory change appears to be an extension of Carey’s work when she further describes the changes in terms of theory enrichment through addition or theory restructuring through deletion or modification.

**Mental model change**
A mental model is perceived as a form of knowledge structure (Gentner & Stevens, 1983) while some see it as a transient representation which is constructed on the spot to deal with a particular situation (Johnson-Laird, 1983; Vosniadou & Brewer, 1992; Vosniadou et al. 1999). According to Vosniadou et al. (1999), such a representation can be manipulated mentally to provide causal explanations for physical phenomena and make predictions about the causal effects of the physical world. Mental models change in different ways as a result of learning (Vosniadou, 1995). An example of a change in a mental model of force is the change from an ‘internal force’ of an object to ‘acquired force’ (Vosniadou et al., 1999). Vosniadou (1995) posits that the change in a mental model is either of the mental model itself or in the underlying structures that constrain it.

**Misconceptions**
We classify the discussion of the underlying causes of misconceptions into four categories: classical view, initial conceptual theory view, mental model view, and general view.

**Classical view**
Ausubel (1968) stressed that preconceptions are tenacious and resistant to extinction while Driver and Easley (1978) state that preconceptions which are deeply rooted in daily experiences are seen as alternative frameworks to provide explanations for physical phenomena.

**Initial conceptual theory view**
According to the initial conceptual theory view, a new conception will be abandoned if it does not appear to be intelligible or plausible (Strike & Posner, 1985). In addition, it is interpreted in the light of the old (Vosniadou & Brewer, 1992; Strike & Posner, 1985) and dissatisfaction with an old conception is absent if it has been proven over and over again and thus explains its tenacity (Vosniadou & Brewer, 1992).

**Mental model view**
Johnson-Laird (1991) highlights the fact that misconceptions about force in physical systems are attributed to: an incomplete model of the domain; an inaccurate model of the
domain; and mere ignorance thus resulting in one’s failure to envisage the situation properly or hold in mind all the various possibilities.

**General view**

Some other general reasons for misconceptions are misleading students’ perceptions (Trowbridge & Dermott, 1980), wrong focus (Anzai & Yokohama, 1984), and inappropriate prior beliefs (McCloskey, 1983a).

**Implications for this research**

In this research, learning is viewed as understanding, problem-solving, and conceptual change. Here, understanding is modelled using a semantic network of interrelated concepts which assumes the form of a causal model. Problems provided in the final system are a combination of well-defined ones and ill-defined ones with specified initial state but with an open final state which has to be predicted by the students themselves. Such predictions have to be justified. It is the interest of this research to investigate these predictions which give insight into their search process as well as their explanatory model. Conceptual change, in this research, is modelled after the schema theory, theories framework and mental model.

**iii. Learning strategies**

**Discovery learning**

As mentioned earlier, discovery learning is one of the strategies that fosters constructivist learning. In the discovery perspective of learning, the learner is viewed as actively discovering regularity and relatedness (Bruner, 1974), or properties of the domain (van Joolingen, 1993). Learners are expected to develop understanding of the domain on their own (Shuell, 1992) and develop skills such as problem solving skills through experimentation and practice (Alessi & Trollip, 1991).

According to Gagné (1966), discovery learning facilitates better retention and transfer. However, he warns that if learners are allowed to discover unaided, learning will end up a slow process and probably unfruitful too due to unnecessary floundering. An example of guided discovery is the Socratic method which has been described earlier. A discovery learning model requires minimal instruction, or intervention which is regarded as inappropriate or counter-productive (Shuell, 1992). On the other hand, Elsom-Cook (1990), an advocate of the guided mode of discovery learning, proposes that the environment be structured in such a manner that constraints imposed are embedded in the environment itself. An example of such a constraint is limiting learners’ choice to options proffered in various menus.
**Exploratory learning**

Interactive learning environments, which shall be described later in this chapter, are exploratory environments because they contain variables to be manipulated and also rules by which the manipulation is constrained. Exploration, here, aims at the acquisition of knowledge through inquiry (Njoo, 1994), or use of a scientific method (van Joolingen, 1993) where a scientific inquiry skill, generally, encompasses the following strategies: exploration, experimentation and hypothesis formation (Shute & Bonar, 1986). The elements for exploratory learning put forth by de Jong (1991) are consonant with that of a scientific inquiry. They are: explore by running experiments, watch the results of the experiments, and draw conclusions from the observations.

**Learning through articulation**

The various modes of articulation (or overt thinking or thinking aloud) are: articulation to self; articulation to peers; articulation to a teacher or system. Self et al. (2000) stress that articulation could occur during or after a thought process or problem-solving activity.

Polanyi (1958) claims that the process of articulation enhances our mnemonic powers, and also assists in the ‘imagination of the inventor’. According to him, articulation highlights the essential characteristics of a situation, thus facilitating ‘imaginative manipulation’. Polanyi (1958) explains some causes of the ‘language-deficiency syndrome’. He maintains that this occurs in a situation where the tacit predominates to the extent that articulation is virtually impossible. According to Polanyi, this is a phenomenon of an ‘ineffable domain’ where we know something in our heads but find it beyond our description. The reasons for such ineffability, in Polanyi’s point of view, are due to ‘defective articulation’ and also the inability to co-ordinate the essential elements in a coherent manner. This concurs with Vygotsky’s notion of spontaneous concepts which saturate our experience but are vocabulary-lean with almost inaccessible formal definitions.

Some reasons for articulation are refinement of theory (Collins & Stevens, 1982), or formulation of ideas (Brown, 1985). In addition, articulation brings about a transformation of tacit knowledge into explicit knowledge, primarily, for inspection and correction purposes (Collins, 1996; Glaser, 1994; Self et al., 2000). Gruber et al. (1995) explain that when cognitive concepts and processes are articulated, they are thereby explicated, and also become an object of reflection which further fosters the generalisation and abstraction processes. Self et al. (2000) call this coupling of the articulation and reflection processes the ‘articulate reflection’ and they suggest that in computer-based learning systems these two processes should go hand in hand in order to effect better learning.
In Ohlsson’s (1992) point of view, to articulate a theory with respect to a concrete event or physical phenomenon means using the theory to explain the phenomenon. Ohlsson argues that theory articulation is a skill which requires complex access to explanation patterns and explanatory procedures. Kuhn (1996) claims that when an explanation for an observed phenomenon is deemed successful, then it forms a paradigm for modelling future explanations and these generic features of a paradigmatic explanation form an explanation pattern. Such patterns, in turn, form a template for generating new explanations in new situations and a procedure applied to fill in this template is known as an explanatory procedure (Toulmin, 1972). Ohlsson (1992) suggests that a combination of scientific theory, explanation patterns and explanatory procedures is a powerful way of learning science.

**Learning through reflection**

Dewey (1960) defines reflective thinking as ‘the kind of thinking that consists in turning the subject over in the mind and giving it serious and consecutive consideration’ (p. 3). To trigger reflection, one must first be placed in a novel, unfamiliar situation which causes perplexity and uncertainty (Dewey, 1960). Reflection that occurs prior to an event is said to be in the pre-reflective stage (Dewey, 1960) and in this preparatory stage, Boud et al. (1985b) claim that students inquire and explore what is required of them. The post-reflective stage occurs after the event when the outcome is mulled over. Boud et al. (1985b) include a phase in between the two, which is during the actual occurrence of the event. Dewey (1960) prescribes several ways reflection can take place: compare and contrast one’s knowledge in the form of a thing or event with that of an expert, compare a thing or event as it is before with what it is after. As mentioned in Section 2.3.1, Lepper et al. (1993) describe how to incorporate the Socratic method to provoke reflection.

Reflection is an essential activity in a learning process. Experience alone is not the key to learning and reflection is one activity that could transform experience to learning (Boud, Keogh & Walker, 1985b; Dewey, 1960; Kolb & Fry, 1975). Kolb’s experiential learning cycle (Figure 2.4) shows that concrete experience is turned into abstract concepts and generalisations through observations and reflection. Reflection facilitates effective problem solving (Collins & Brown, 1988; Lepper et al., 1993) and also leads to new understanding and appreciation (Boud et al., 1985c; Dewey, 1960). Figure 2.5 illustrates how in an understanding process, a piece of information is transformed into a more organised piece of knowledge through reflection. It helps one transcend beyond the surface learning, thus enabling one to grasp the deep meaning of a concept and to integrate it with prior knowledge through the assimilation and accommodation processes. Dewey (1960) maintains that reflection impels inquiry about the reliability of one’s
belief, an evaluation of its value, the gathering of data to confirm or refute it, and the justification or rejection of its acceptance. Consequently, through reflection, distortions in one’s beliefs and errors in problem-solving can be corrected (Merzirow, 1990b).

**Learning through reasoning**

Holyoak and Nisbett (1988) maintain that the act of reasoning involves the use of rules about events in a particular domain. Inferential rules are context dependent and they encompass general rules about causal relations that exist in that particular domain. Successful learning through reasoning, according to Vosniadou & Ortony (1989), largely depends on one’s ability to identify the most relevant bodies of knowledge that reside in the memory. In this section for reasoning, we explain, though not in detail, relevant types of reasoning such as experiential reasoning, common-sense reasoning, scientific reasoning, analogical reasoning, and qualitative reasoning.

**Experiential reasoning**

Experiential reasoning is closely related to its outcome, experiential learning. One of the crucial tenets for experiential learning as outlined by Miller and Boud (1996) is that experience is the foundation or stimulus for learning. If we relate to Kolb’s experiential learning cycle again, this form of experience is confined to concrete experiences alone. As shown in Figure 2.4, we have included the act of reasoning alongside with observations and reflections as the media for transforming concrete experiences to abstract concepts and generalisations. Thus, in this research, we define experiential reasoning as reasoning with knowledge constructed through concrete experiences, albeit everyday experiences or laboratory experiences.

**Common-sense reasoning**

In Qualitative Physics, common-sense reasoning is typically the type of reasoning employed to reason about physical systems. Common-sense reasoning, according to Resnick (1989) is the act of drawing on the repertoire of common-sense knowledge about the physical world to predict and explain a phenomenon. Buchanan & Wilkins (1993) point out that inference drawn from common-sense reasoning is often ‘mentally effortless’. Forbus (1990) implies that with common-sense reasoning, one can ‘reason fluently’ about a phenomenon without first having to grasp its underlying formalisms. In this research, we perceive common-sense reasoning as reasoning with the model alone without having to resort to any quantitative equations nor retrieving relevant prior knowledge.
Scientific reasoning

Scientific reasoning, according to Klahr and Dunbar (1988), involves experimentation and hypotheses formation. Their conception of dual space search during scientific reasoning comprises an experiment search and a hypothesis search. In the former, hypotheses are first formulated based on prior knowledge, followed by conducting experiments to confirm or refute the hypotheses formed. As for the latter, the order of events is the reverse with experiments preceding the formulation of hypotheses and rule discovery through generalisation is its primary aim. Basically, inductive reasoning and deductive reasoning are different facets of scientific reasoning.

Holyoak and Nisbett (1988) define inductive reasoning as drawing inferences in order to generate hypotheses or generalisations. Thus, this is exemplified by the experiment search that has just been mentioned. Holyoak and Nisbett cite instance-based generalisation as an example of rule discovery where inferences are drawn from one or more instances. Evans (1990) views inductive inferences as not only a means to infer general rules but also for classifying observations of specific observations into categories, thus resulting in the acquisition of the knowledge of concepts as well as categories.

Deductive reasoning, on the other hand, involves inferences being made from general principles to particular cases. It is drawing logical conclusions based on a set of facts or supposed facts known as suppositions (Garnham & Oakhill, 1994). Mayer (1992) lists three types of deductive reasoning: categorical reasoning, conditional reasoning and linear reasoning. However, only the second category is relevant here because it assumes the cause and effect relationship. An elementary form of such logical reasoning to signify a conditional relation is If $p$, then $q$ or if not $p$, then not $q$’ where ‘$p$’ is some antecedent condition while ‘$q$’ is some consequent condition.

Analogical reasoning

Analogical reasoning involves the transfer of relational information from a base domain to a target domain (Vosniadou & Ortony, 1989). Success of an analogical transfer depends on the perceived similarity between the domains. Vosniadou and Ortony emphasise the similarity in surface properties as well as the relational structure of the base and target domains while Gentner (1983) stresses the structural similarity. Surface similarity in problems refers to the surface content that is alike with common details shared while structural similarity refers to the correspondence between the relations of objects in one problem with that of another problem.
In the problem-solving context, analogical reasoning is defined as a process which involves the abstraction of a solution strategy from a previous problem and relating it to the given information in the new problem to be solved (Mayer, 1992). Mayer prescribes three conditions for a successful analogical transfer: recognition, which involves the identification of a potential analog (base) from which to reason; abstraction, where a general structure, principle or procedure from the base is abstracted; mapping, where knowledge acquired is applied to the target. He suggests that the mappings that can occur between two domains are of similar features and relations, or of dissimilar features but similar relations.

**Qualitative reasoning**

de Kleer and Brown (1984) argue that classical physics only provides quantitative constraints in the form of equations which neither support suggestive explanations nor provide insights because they are, in essence, devoid of causal information. diSessa (1987) highlights the fact that though generally, students can recite quantitative forms of physics laws (e.g. F=ma), and solve quantitative physics problems well, they may not be able to view how these laws fit into the physical world. Therefore, diSessa (1987) argues that qualitative understanding of physics laws is essential to understanding the physical world. Ploetzner (1995a) maintains that in order to effect more successful quantitative physics problem solving, relevant qualitative and quantitative physics knowledge have to be invoked, and co-ordinated.

According to de Kleer & Brown (1990), if \( a \) is an arbitrary value then the ‘quantity space’ of a variable \( x \) could be \( x < a, x = a \) or \( x > a \). However, the most important property of a qualitative variable is if it is increasing, decreasing or unchanging. Its corresponding derivative has a quantitative space of three values: + (for increasing \( x \)), − (for decreasing \( x \)), or 0 (for constant \( x \)).

Ploetzner and Spada (1992) outline three levels of qualitative reasoning. They are:

**First level: ‘Very global’**

In this level, it merely states that a variable is related to another. An example is *A is related to B*.

**Second level: ‘Qualitative relational’**

It states that two variables are qualitatively related to each other. An example is *If A increases then B increases*.

**Third level: ‘Quantitative relational’**

It states that two variables are quantitatively related to each other. An example is *If A doubles then B doubles*. 
iv. Implications for this research

In this research, students are encouraged to articulate their thoughts. As mentioned earlier, an Articulation-cum-Reflection tool is provided for such a purpose, especially in a language deficient domain such as buoyancy. Articulation is coupled with reflection so as to effect better learning. As mentioned earlier, both the systems are also problem-solving based so as to provoke reasoning. Here, the students’ reasoning strategies to be examined are: experiential reasoning, common-sense reasoning, scientific reasoning, analogical reasoning and also qualitative reasoning. Once again, qualitative graphs are provided to facilitate qualitative reasoning and subsequently, foster a better qualitative causal understanding of the domain. Here, the model used to examine the students’ level of qualitative reasoning comes from the integration of both the models created by White & Frederiksen (1987a) and Ploetzner & Spada (1992).

2.3.3 Related computer-based learning environments

A number of related existing systems have been selected and described followed by highlighting relevant features for the design of the two computer-based learning environments in this research. The discussion of this section is divided into interactive learning environments, non-tutoring systems, and Socratic dialogic systems.

i. Interactive learning environments

Van Joolingen (1993) defines the term interactive as ‘a dual-way communication between the learning material and learner, which is of mixed initiative’ while Sewell (1990) does not view interaction as simply an exchange but a meaningful one which aims to effect learning. The key feature of an interactive medium, as Laurillard (1993) points out, is the provision of intrinsic feedback for student’s actions. However, Sewell views an interactive learning environment as not only reacting appropriately to students’ evaluated responses but also providing the facility for students’ manipulations. This appears to be one of the salient features of a simulation discussed below. Papert (1980) adopted a rather radical perspective when he stated that in an interactive learning environment, learners are active and are ‘constructing architects of their own learning’ (pp. 122), thus implying an absolute learner locus of control. Such a learner characteristic is the trademark of a microworld which is discussed later.

Simulations

A simulation, in general, is a system which models some aspect of the real world system through imitation or replication. The notion of a simulation discussed in this context is not a vicarious but an interactive one. Alessi and Trollip (1991) perceive it as a powerful teaching tool while for de Jong (1991), a simulation is a tremendous investigative tool for promoting exploratory as well as
Chapter 2 Review of Related Literature

interactive learning. Such active learning is made possible when users are given the opportunity to make inputs to the model through the manipulation of selected variables. Laurillard (1993) argues that this is the pre-requisite characteristic of a simulation. Subsequently, the model runs, and displays results accordingly and such intrinsic feedback is the reason why a simulation is considered interactive. However, the simulation merely responds to an action with neither comment nor discussion, thus leaving the student to interpret the feedback. Consequently, there is a risk of arriving at a wrong conclusion. The phrase ‘model some aspect of the real world system’ needs a closer look. Such an over-simplified model might result in a misguided impression of real world events or situations (Sewell, 1990) and misconceptions or incomplete knowledge (Goodyear & Tait, 1991). On the other hand, a simulation provides students the opportunity to explore a variety of ‘realistic’ situations which are otherwise dangerous in real life. Ideal situations such as frictionless worlds can be created for the exploration of forces (diSessa, 1982). In addition, abstract situations can be concretised as in the aforementioned case of Teodoro’s (1994) visual representation of velocity for the purpose of facilitating a better conceptual understanding.

Three examples of simulations will be described: STEAMER (Hollan, Hutchins, & Weitzman, 1984), a classic example of simulation for training purposes; Smithtown (Schauble, Glaser, Raghavan & Reiner, 1991), for representing complex relations; QUEST (White & Frederiksen, 1987a), a simulation for instructing students about physical devices.

STEAMER affords an intelligent and interactive graphic simulation of a steam plant developed for use in propulsion engineering courses. Conceptual fidelity and not physical fidelity is the focus of the system and together with the provision of control, manipulation and monitor facilities, it aims to assist students to understand and reason about the dynamics of such a complex physical system.

The graphical interface in STEAMER portrays the state of its components through the change of colours and the transmission of signals characterises the internal behaviour of the system. However, the first derivative of this signal at an instant is more meaningful and useful than its absolute value. The first derivative here, as in Calculus, reveals three possibilities: increase, decrease, or constant in value. In order to represent this information in a more explicit manner, Hollan et al. create a signal or derivative icon. These signal icons are utilised to provide a qualitative explanation for the behaviour of the system. A quantitative Cartesian graph is first plotted for the absolute value of a variable against time. Correspondingly, a signal icon is used to depict qualitatively and graphically, the rate of change of the variable. As a result, as illustrated
in Figure 2.6, the quantitative graph is translated into a series of qualitative signal icons. Hollan et al. emphasise that such a series of icons is appropriate for assisting novices develop qualitative causal explanation for the behaviour of a system such as the automatic boiler control system. They argue that it is particularly difficult to use natural language to explain the dynamic behaviour of systems, due to its serial nature. Therefore, a qualitative graphical representation better facilitates a causal explanation of the behaviour of the system as well as explicitly displays the qualitative relationships of the underlying model.

Figure 2.6: A series of signal icons (adapted from Hollan et al., 1984, p. 121)

Smithtown (Schauble, Glaser, Raghavan & Reiner, 1991) is a computer-based simulated laboratory for microeconomics which supports scientific inquiry about complex relationships in the domain. Basically, it hinges on the hypothesise-test-revise strategy which is pivotal in scientific enquiry. Exploration in this simulation begins with the selection of a scenario in the form of a market for service or goods. The next action is to manipulate one or more of the following independent variables: price of the good, population, and the number of suppliers followed by making one or more predictions about their outcomes. These outcomes are the causal effects on related dependent variables such as supply, demand, shortage, or surplus. When the simulation is run, it displays the effects of the changes made on the related dependent
variables. The student can use the available graphing tool to transform the given feedback into graphs or manipulate them through the use of a spreadsheet-like table package. After several experiments, the student states the discovered underlying principles or laws whose accuracy is once again evaluated by the computer program.

QUEST (White and Frederiksen, 1987a) is influenced by de Kleer and Brown’s work on qualitative reasoning. It is a learning environment centred on an interactive simulation for instruction about physical devices. The goal of this system is for the students to understand the underlying general principles of the electrical circuits, predict states of components and subsequently, perform some troubleshooting operations. It emphasises the use of qualitative models to support causal explanation. Different levels of qualitative reasoning (White & Frederiksen, 1987a) are employed to explain the behaviour of an electrical circuit. The lowest level is the ‘zero order’ which is the simplest form of qualitative reasoning. Based on the simple circuit in Figure 2.7, a question to exemplify this level of reasoning is to ask if the light bulb in the circuit will light up or not. The ‘first order’ qualitative reasoning is more sophisticated because it incorporates qualitative derivatives. A question to invoke this level of reasoning is to ask if a change in the variable resistor will make the light bulb brighter or dimmer. In this case, it concerns the causal effect of a change in a component on another in the system.

![Figure 2.7: An elementary electrical circuit](image)

**Microworlds**

Laurillard (1993) points out that the term microworld is always confused with simulation because the former is a feature of simulation and at the same time, allows the user to act within a ‘little world’ which is its distinct characteristic. Papert (1987) regards a microworld as a ‘little
slice of reality’. This means that a microworld is reality itself while a simulation is just a representation of reality. Thus this explains why a microworld is different from a simulation though the difference could be considered rather hazy. It means, literally, a ‘tiny world’ inside which a student can explore alternatives, test hypotheses, and discover facts that are true about that world. Essentially, this is the central idea of the constructivist educational philosophy, which neither teaches nor provides any instruction. As mentioned earlier, the learner here is regarded as the sole designer of his own learning.

Lawler and Lawler (1987) emphasise that the creation and manipulation of an object is one of the important functions of a microworld. In the Logo microworld (Papert 1980), the object created to inhabit this world is a small turtle. It can be directed to move around via typed commands through the computer. As it moves, it simultaneously creates shapes or patterns. Papert (1980) argues that though this world is strictly limited by the turtle’s movements and drawing capability, it offers a rich environment to facilitate a child’s unfettered exploration.

Dynaturtle is an enlarged concept of Papert’s geometry Turtle, which is designed to replace the concept of a ‘particle’, an abstract entity in Newton’s laws (Papert, 1980). It is more dynamic with its state defined by two velocity components coupled with the two original geometric components, position and heading, which are inherent attributes of the geometry Turtles. The physics microworld which is developed with Dynaturtle gives children the opportunity to explore and discover Newtonian laws without having to learn the formalisms first. Thus, Papert (1980) suggests that such a microworld is an incubator of Newtonian physics knowledge.

Papert’s microworlds (1980) support creativity while ThinkerTools (White, 1988) focuses on problem-solving by providing a game-like problem solving environment. Just like Papert’s physics microworld, it facilitates scientific inquiry with a ‘dot’ as its created object. The behaviour of this ‘dot’ can be manipulated through one of the following fundamental concepts in Newtonian mechanics: impulse, velocity, force or acceleration. Two of the ultimate goals are that students understand what these abstract yet physical constructs are and at the same time discover the causal relationships between them.

ii. Non-tutoring environments

Unintelligent Tutoring Systems (UnITS)

Unintelligent tutoring system is a term coined by Nathan, Kintsch, and Young (1990) to describe their system, ANIMATE. Unlike an intelligent tutoring system (ITS), it has little or no artificial intelligence, and neither does it have any student model nor expert domain module. Primarily, it
provides well-designed cognitive tools to encourage self-regulation, self-diagnosis, reflection and enhanced problem-solving performance (Derry & Lajoie, 1993). In the event of an error, the learner’s actions should: observe the effects of his actions, harness his prior knowledge to identify solution errors, re-examine his pre-conceptions, hypothesise the cause of his errors, propose a modified solution, and test it again (Nathan, 1991). Possibly, the error is corrected through multiple iterations. Due to the student’s pivotal role as a diagnostian, Nathan (1998) even cites the Logo programming environment (Papert, 1980) as the epitome of an unintelligent tutoring system.

In our opinion, the term Unintelligent Non-tutoring System (UNS) is more appropriate than UnITS because it does not have any tutoring facility. Based on a review of related literature, using feedback as the essential criterion, we classify unintelligent and non-tutoring systems into three categories: UNS with intelligent feedback, UNS with situational feedback and UNS with no feedback.

**UNS with intelligent feedback**

Reusser (1993) argues that the tutoring component is vital to avert frustrated feelings in the event of an error or impasse. A suggestion put forth is that in such situations, help or feedback be automatically given or invoked on request. An example of such a system is HERON (Reusser, 1993), a graphics-based instructional tool which aims to facilitate and foster self-directed understanding as well as solving complex mathematical word or story problems. HERON is unintelligent because it does not perform any cognitive diagnosis. Instead, it performs a behavioural analysis of student’s overt actions based on a cognitive task analysis. Thus, feedback is accorded based on a detailed analysis of the task space mapping it onto student’s constructed solution trees. This is the reason why we consider such feedback intelligent, though the notion ‘intelligent’ greatly differs from that of normal ITS.

The system was evaluated on fifth-grade students who worked in pairs. The results revealed there was an improved understanding and complex mathematical problem-solving performance (Staub, Stebler, Reusser, & Pauli, 1994). However, a question that is left unanswered is whether the provided cognitive tool is equally effective in the individual mode of exploration.

**UNS with situational feedback**

ANIMATE (Nathan, Kintsch & Young, 1990) is an interactive learning environment designed to

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2 ‘Our’ refers to the author’s throughout this thesis
support introductory word algebra problem solving and focuses on comprehension-based problem solving. In contrast to HERON, it cannot assess students’ solutions, has no knowledge of the correct answer, or even of the problem that is being solved (Nathan, 1998). When interacting with ANIMATE, a student is given a narrative problem situation. Solutions in the form of algebraic equations are constructed followed by the computer providing animation based on the student’s solution. If an unexpected behaviour occurs during the animation, this implies an erroneous solution. The student, subsequently, has to perform error diagnosis and recovery. Empirical evaluation of ANIMATE (Nathan, 1998) reveals a great gain in problem solving and inference-making performance. An analysis of the problem-solving process indicates that the provision of support for students’ situational model construction in the form of algebraic equation construction, enhances their inference-making abilities during problem solving. The two types of errors investigated are: omission error where necessary components of a problem solution have been omitted; misformulation error where all necessary components are included but are wrongly formulated. Nathan (1998) claims that ANIMATE users demonstrate a decrease in the number of occurrences for both omission and misformulation errors for algebraic expressions.

**UNS with no feedback**

The Envisioning Machine (Roschelle, 1986, 1991) is an example of UNS with no feedback. The Logo programming environment (Papert, 1980) should come under this category too. The Envisioning Machine (EM) is a direct-manipulation and graphical simulation for the abstract vector concepts of velocity and acceleration.

Velocity and acceleration, in EM, are given neutral names ‘the thin arrow’ and ‘the thick arrow’ respectively, instead of their formal terms. In its screen are two windows: ‘Observable World’ and ‘Newtonian World’, as illustrated in Figure 2.8. The former displays a simulation of a ball moving across the screen while the latter depicts a particle with velocity and acceleration vectors in the form of the two types of arrows mentioned earlier. The students interacting with EM are requested to make the motions in both the windows the same. This is made possible by adjusting the lengths of the vector arrows in ‘Newtonian World’ and running the simulation in this window. The students self-evaluate whether the motions displayed in both the windows are the same. This means that the student has to develop his own criteria for such judgement. In other words, the computer response to the student’s actions does not inform him if he is correct or otherwise and this is the reason why we classify EM as UNS with no feedback. Roschelle (1986) claims that more than half of EM users in his investigation eventually constructed a knowledge system that approximated a scientific understanding of velocity and acceleration.
In conclusion, we list down three principles of an unintelligent non-tutoring system. They are:

**Locus of control**
In an UNS, a student is an autonomous learner who decides which knowledge is relevant for the situation, and observes the consequence of his decision. In the event of an error, he conducts a self diagnosis by evaluating and reflecting on his decision followed by bug repair.

**Feedback**
Error-discovery, error-recovery, and their association with types of given feedback is discussed. The three categories of feedback addressed here are: immediate, delayed or no feedback. Empirical evidence reveals that immediate feedback interferes and hinders students’ diagnostic reasoning because they are overly dependent on the given feedback. On the other hand, error-discovery performance is shown to improve with delayed feedback in domains such as navigation games (Lewis & Anderson, 1985). Ohlsson and Rees (1991) demonstrate how conceptual learning and error-recovery in the domain of mathematics can occur with neither feedback nor instruction.

**Meaningful learning**
Meaningful learning occurs when students could invoke their relevant prior or experiential knowledge and integrate them with the new knowledge provided in system.

### iii. Socratic dialogic systems
A dialogic system engages a learner in a dual-way communication. We use the term ‘Socratic dialogue’ to refer to the act itself and ‘Socratic method’ to refer to the pedagogy. According to Laurillard (1993, p. 90) ‘the goal for Socrates is Truth to be achieved through philosophical inquiry’. In other words, ‘what it is’ is the gist of a Socratic Dialogue where the tutor first sets a non-negotiable goal that is used to guide the learner. The Socratic method is an indirect method hinged on inquiry and is not prescriptive. Students are encouraged to articulate their thoughts. Instilling a higher mental process is its chief goal by compelling the student to probe deeper through the perceivable surface structure so as to gain a deeper understanding of a context. The essence of the Socratic method is to attempt to challenge a students’ belief by posing questions,
leading the student step by step till he recognises his ignorance or false beliefs and thereby, revise his belief or change. The notion of a Socratic method can be summarised as follows:

‘ …the tutor does not teach a subject by direct exposition, but leads the student by successive questions to formulate general principles on the basis of individual cases, to examine the validity of her own hypotheses, to discover contradictions, and finally extract correct inferences from the facts she knows.’

(Wenger, 1987, p. 39)

However, a problem that may arise is that it highlights the error without explaining why. Laurillard (1993) argues that the Socratic method is extremely authoritarian and does not qualify as a tutorial method.

A classic system that exemplifies such a paradigm is WHY (Stevens & Collins, 1977). WHY is anchored on the Socratic method which aims to guide a student’s reasoning process through dialogues. It has two capabilities: approximated natural reasoning and tutorial dialogues. Meteorology is the domain opted for in WHY because causal relations tightly bind its facts. The main focus of the domain knowledge is the investigation of rainfall processes. However, its natural-language processing capabilities are relatively simple and its Socratic tutorial strategy is rather complete and sophisticated. WHY comprises about 60 production rules (Collins & Stevens, 1982). Such rules include local decisions the tutor ought to make to conduct a dialogue. An example of a local decision is what the tutor should ask or propose after a student’s response. Wong et al. (1998) refine all these production rules by adding some new conditions and incorporate them into the design of the inquiry tutor for TAP (Tutoring Agenda Planner) which is an intelligent tutoring system. The inquiry tutor conducts a Socratic dialogue to help students develop systematic reasoning skills through the formulation, testing and debugging of hypotheses.

Lepper et al. (1993) demonstrated how the Socratic method may be incorporated into simple mathematical problem-solving. Here, the tutor seeks to create pairs of problems based on two possible guidelines. Firstly, the pair is either closely related or require similar solutions and secondly, the pair consists of seemingly similar problems that yield different results or involve different processes. They suggest that as a pair of problems are posed to students, they be asked to compare and contrast the different problems, and to predict the outcomes or solutions. An excerpt abstracted from Lepper et al. (1993) illustrates the implementation of the suggested strategy:

Student: Write $137+77$ (presented in writing) with 77 on bottom. (solves correctly)
Tutor: Absolutely right. How would you write it if you wanted to put 77 on top?
Student: Like this. (writes correctly as requested)
Tutor: Do you think it’ll come out the same as this [previous problem], or not?

(Lepper et al., 1993, p. 94)
This means that the student has to concurrently make four different mappings: similar or dissimilar structure of the pair of problems, or solutions, and each problem to its respective solution. Such mappings aim to impel the student probe beyond the surface similarity to a deeper level similarity, where physical laws or principles govern.

Another suggestion put forth by Lepper et al. for implementing a Socratic method is to ask students directly for alternative ways to solve or present or represent the same problem they have just correctly completed, especially when that alternative may be more elegant or effective.

iv. Implications for this research
The computer-based learning environments designed for this research are interactive learning environments which simulate the laboratory models. The laboratory model itself relates loosely to a microworld, and it aims to facilitate students’ exploration. Both the systems to be described in Chapters 3 and 4 are UNS, with the prototype providing indirect feedback while the final system affords three types of feedback: no feedback, delayed feedback, and situated feedback. To reiterate, such systems are designed to elicit knowledge, invoke students’ prior knowledge and foster self regulated error-discovery and error-correction. Pictorial Socratic Dialogue\(^3\), instead of the typical textual one, is incorporated into the prototype environment of this research to provoke reflection. The rationale for selecting a pictorial representation is due to evidence of a limited language processing revealed in WHY. Here, the pictorial communicative mode is more precise and efficient and it is certainly more suitable for a vocabulary-lean domain such as buoyancy.

2.3.4 Relevant human-computer interaction issues
Only two related issues of human-computer interaction are touched on in this section. They are direct manipulation, and representations which encompass external as well as multiple-linked representations.

i. Direct manipulation interface
A direct manipulation interface is considered user-friendly because graphical objects can either be manipulated directly or through labelled button presses. Its advantage is that users get immediate visual feedback, and actions are rapid and reversible. (Marongo & Schneiderman, 1987).

\(^3\) The phrase ‘Pictorial Socratic Dialogue’ has been coined to refer to dialogues involving only graphics (e.g drawings of objects or Cartesian graphs)
ii. Representations

One of the proposed principles for the design of computer-based cognitive tools for learning problem solving as put forth by Reusser (1993) is the provision of intelligible and effective representation tools for thought and communication. Such tools can assume the following forms: Cartesian graphs, diagrams, spreadsheets, symbol systems, or scientific notations. For a representation to be effective, Reusser suggests that it allows the students to view their manipulations, and fosters rapid recognition as well as retrieval of relevant information. This applies to the two specific examples: external and multiple-linked representations as well.

**External representations**

External representation is a tool to help students externalise their mental models (Reusser, 1993) for inspection, analysis, comparison, communication, and further reflection (Glaser et al., 1996; Greeno, 1987). Typically, in a laboratory, plotting of quantitative graphs follows the task of data collection or tabulation of results and it is utilised as an analytical tool for uncovering the underlying patterns (Leinhardt et al., 1990). Graphs, according to Pisan (1995), can be used to represent relationships between variables where points, lines and areas represent conceptual relationships in the domain.

On the other hand, since a graph is a specialised form of diagrammatic representation, and also a symbolic system with its own symbols and rules, it is not surprising if some students have difficulties associated with construction and interpretation of graphs (Berg & Smith, 1994). Explaining concepts conveyed by the graphs could be a problem too (Beichner, 1990). Thus, Brna, Cox and Good (1996) express the concern that, in certain cases, learners will face problems if they have to learn some knowledge represented with the help of a diagrammatic external representation system and at the same time learn about the representational system itself.

For the purpose of this research, Cartesian graphs are selected to be the means of external representation because it is a familiar as well as a powerful expressive tool. Qualitative graphs allow students to focus on the causal relationships between the variables, provide explanation for the established relationship, and discover the underlying law.

**Multiple-linked representations**

Multiple-linked representations present information in more than one format, with the intention that one representation complements the other. The difference between the two notions is that in the latter, the learner can modify the information being presented in one format and at the same
time, see the concurrent effect of the change reflected in each of the other representations being used. An example of a multiple-linked representation is the spreadsheet system in Microsoft Excel where graphs are plotted based on the data in the spreadsheet. Any change in the value of a cell in the spreadsheet effects a change in the graph.

An example of a learning environment with the multiple-linked representational feature in its interface is 4M: CHEM developed by Kozma et al. (1996) for Chemistry. Students can perform a ‘virtual’ experiment by heating a test-tube containing a ‘white substance’ which changes to red when ‘indirectly heated’. Concurrently, other representations depict appropriate changes such as the changes in kinetic model (billiard ball), a graph of partial pressures against time, and a symbolic representation of the dynamic equilibrium. The aim of this system is to examine the role multiple-linked representations play in fostering novices’ understanding of chemistry and chemical equilibrium. Results of a formative evaluation reveal a significant gain in the understanding of chemical equilibrium. Also, it shows a reduction in misconceptions relating to chemical equilibrium as well as effect of temperature and pressure on equilibrium.

iii. Implications for this research

Direct manipulative interfaces chosen for this research are intended to facilitate exploration. Qualitative graphs are employed as the external representations to facilitate a pictorial Socratic dialogue for the purpose of this research. Multiple-linked representations embedded in the prototype interface enables the user to observe the link between the state of the block in the model and the reading of the spring balance. This is further described in Chapter 3.

2.4 Conclusions

Buoyancy is a domain with a large semantic network of facts and causal relationships. Consequently, an interactive learning environment developed for such a domain enables students to explore the context richly. Great emphasis is given to the role of prior knowledge in helping students learn. Thus the situations incorporated in the environments are familiar yet novel. The strategies of articulation, reflection, and reasoning play a central role of effecting better learning. The three conceptual change theories (schema change, theory change, and mental model change) provide the framework for evaluating any learning that has occurred.