Formal Reasoning and Conceptual Change

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Formal Reasoning and Conceptual Change

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ABSTRACT

In this study we addressed the following questions over three studies. In **Study 1** we addressed the questions, "*What formal reasoning skills do CÉGEP science students have?*" and *What are the relationships among motivational factors, achievement, and formal reasoning?* In **Study 2** we addressed the question "*Does an intervention designed to improve students' formal reasoning and attributions enhance student performance?*" In **Study 3** we addressed the question "*Can we measure changes in students' conceptual structures?*"

In **Study 1** we found that students in Technology Programs were less skilled than students in Pre-university Science Programs with only 48.5% attaining formal reasoning level compared to 76.8%. Moreover, less than 5% of the Technology Program students had attained the high formal reasoning level compared to 28% of the Pre-university students. Female students were less skilled at formal reasoning than male students, with only 64.5% attaining the level of formal reasoning compared to 73% of the male students. Female students were significantly less skilled than male students at proportional reasoning. Students who had higher formal reasoning skills also had higher self-concept, believed that they controlled their academic success (rather than luck or others), and achieved higher grades in their CÉGEP science courses. In **Study 2** we found that an intervention incorporating explicit teaching of proportional and combinatorial reasoning and attributional retraining increased students' skill at reasoning about proportions and combinations butt did not influence students' self-concept, academic self-esteem, nor perceived academic control. The intervention increased students' performance on a lab test question but not on a test on evolution. In **Study 3** we found that all three methods of inferring students conceptual structures (coded answers to multiple-choice questions assessing specific misconceptions in the chemical nature of water and osmosis; essays on the same two topics coded to measure the same misconceptions; and cognitive maps produced from similarity ratings on two sets of terms on the same two topics analyzed using a scaling technique (Pathfinder analysis) could provide information on students' conceptual structures. Similarity ratings are easy to administer and analyze, give readily interpretable representations (cognitive maps) of students' conceptual understanding, and as shown in a follow-up study on evolution sensitive to instructional interventions.

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INTRODUCTION

1.1. Problem Statement

Science education in North America is in a crisis. The diminishing enrollment in science (Tobias, 1990), high rate of attrition (Conseil des Colleges, 1988) and poor student performance (Culliton, 1989; Lewin, 1989; Grant, 1990) indicate serious problems with science education. Moreover, science appears to be more accessible to certain groups of the population, i.e., male students belonging to the dominant scientific culture, *i.e.*, similar to science faculty (Tobias, 1990). These deficiencies need to be addressed, since a lack of basic science literacy has negative effects not only on the scientific community but also on economic development (Roger, 1983; Brooks, 1989; Walberg, 1991).

Many researchers consider that the underlying problem in science education is that many students do not acquire a meaningful understanding of science (Eylon & Linn, 1988; Cavallo, 1991; Alexander & Kulikowich, 1992). Students tend to rely on memorizing isolated facts and procedures rather than on relating ideas and constructing a coherent body of scientific knowledge. They also have difficulty in abstracting key ideas, discerning relationships between ideas, and integrating these ideas to their prior knowledge to form a coherent framework (Novak & Gowin, 1984; Dansereau, 1990). Thus, students have difficulty transferring what they have learned in the classroom both to other courses in the same discipline and to "life" situations. The Ministry of Education has recognized this problem by introducing a number of projects intended to increase student success and to encourage science faculty to require their students to integrate their knowledge across disciplines and solve novel problems (MEQ, 1997).

Meaningful learning, in contrast to rote learning, is a process whereby learners actively wrestle with new ideas, evaluate their prior knowledge, and reconstruct their conceptual structures to include the new knowledge (Ausubel, 1963; 1968; Novak, 1988; Roth, 1990). Thus, meaningful learning requires that students change their conceptual structures. However, studies from a variety of perspectives (misconceptions, alternative conceptions, naive beliefs, *etc.*) have shown that college students often have great difficulty in doing this (Driver & Easley, 1978, Caramazza, McCloskey, & Green, 1981, Pintrich, Marx, & Boyle, 1993; Chinn & Brewer, 1993). In this research report we use the term misconceptions to refer to "any conceptual idea whose meaning deviates from the one commonly accepted by scientific consensus" (Cho, Kahle, & Nordland, 1985, p 709).

Ausubel (1963, 1968) proposed a theory of meaningful verbal learning in which he stated that meaningful learning occurs when learners acquire new information about a topic, evaluate the new information in relation to what they already know, and incorporate it into existing conceptual structures. Expertise in the domain occurs as learners perceive the general principles of the domain and revise their conceptual structures accordingly. Thus, since the concepts are linked to general principles, students can more easily transfer their expertise to novel problems. Many researchers (*e.g.*, Ausubel, 1963; Novak, 1988; Roth, 1990; Pintrich, Marx, & Boyle, 1993) have suggested that at least three conditions are required for meaningful learning and conceptual change to take place. First the classroom instructional context must encourage meaningful learning and conceptual change. Second, the learner must have the appropriate motivational attitudes and behaviours. Third, the learner must have the appropriate prior knowledge and cognitive skills and strategies. That is, learners must believe that conceptual change is worth while, want to reconstruct their understanding, and have the necessary knowledge and skills to do so. When any one of these requirements is lacking, conceptual change and meaningful learning does not take place. Each of these conditions is briefly described below. However, the focus of the research reported here is on the third factor, namely the cognitive skills (formal reasoning) and conceptual structures of CÉGEP science students.

Classroom instructional context. Researchers (Garner, 1990; Meece, Blumenfeld, & Hoyle, 1988) have proposed that classroom contextual factors, such as task, authority, and evaluation structures, influence learning. Garner suggests that many classroom contexts are inappropriate for fostering conceptual change. Such factors as authentic and challenging task structures, authority structures that allow for student choice and challenge, evaluation structures that promote mastery, classroom management practices that promote effective task engagement, and teacher modeling of scientific beliefs and reasoning are believed to foster meaningful learning and conceptual change.

Concerns about fostering meaningful learning in sciences classes have lead to revisions in science curricula and the development of alternative pedagogies which incorporate some of the above conditions (Eylon & Linn, 1988; Wallberg, 1991; d'Apollonia & Glashan, 1992; d'Apollonia, De Simone, Dedic, Rosenfield, and Glashan, 1993). These innovations are attempts to create learning environment in which students become meaningfully engaged in classroom tasks. Many innovative projects integrating technology (e.g., Learning by Design from Georgia Institute of Technology, BioWorld from McGill

University, Quest Atlantis from Indiana University) have been developed to foster deeper learning. A complete list with contact information can be obtained from LESTER (2004).

Motivation. Researchers have also studied the role of motivational and attitudinal factors in meaningful learning (McKeachie, Pintrich, Lin, Smith, & Sharma, 1990; Pintrich, Brown, & Weinstein, 1994). For example, Pintrich, Marx, and Boyle (1993) suggest that the appropriate epistemic beliefs, mastery goals, personal interest, utility value, importance, self-efficacy, and control beliefs are necessary for conceptual change. Moreover, students may not use the learning strategies they possess because they may make inappropriate causal attributions, or have inappropriate learning goals (Garner, 1990).

A number of interventions have been designed to change post-secondary students' motivational patterns. For example, attributional retraining programs, in which students view video tapes depicting that poor academic success is due to lack of effort and not necessarily to lack of ability, have significantly improved both motivation and academic performance (Forsterling, 1985). However, McKeachie *et al.*, (1990) warn that such motivational interventions may be detrimental to students in the long run. Training students to attribute failure to lack of effort and to persist at difficult tasks "may not be helpful if the student does not actually possess the skill needed to complete the task" (McKeachie *et al.*, 1990, p 75).

The cognitive skills deficit model (Tobias, 1985) suggests that certain students have poor microlevel (*e.g.*, rehearsal) and macrolevel (*e.g.*, metacognition) cognitive processes. Such students are often anxious when learning new material. Their anxiety causes them to become frustrated, disrupt the class, and withdraw from active learning. They subsequently perform poorly. Such students are often described as lacking motivation; however, the underlying problem may be a lack of the necessary cognitive skills. Thus, in this research, we concentrated on cognitive skills and measured motivation to statistically control for variations in motivational patterns.

Cognition. In this research we adopted a constructivist theoretical perspective on learning first proposed by Piaget and his colleagues (Piaget, 1954; Inhelder & Piaget, 1958). Piaget and his colleagues maintained that, as individuals interact physically and mentally with their environment, they construct mental models (conceptual structures) by which they "make sense" of the world. Meaningful learning occurs when learners alter these conceptual structures in order to resolve discrepancies between their mental models and new experience. Piaget maintained that individuals move through fixed developmental stages as a result of both biological maturation and interactions with conflicting aspects of the environment. Piaget (1972) suggested that although all learners are genetically programmed to develop formal reasoning, this cognitive development can *only* occur under the appropriate environmental conditions.

1.2. Research Objectives

Thus, we designed several studies to address the following research objectives:

1) To measure the formal reasoning skills exhibited by CÉGEP students enrolled in a science course;
2) To determine whether formal reasoning skills are associated with students' success in high-school and CÉGEP science courses;
3) To determine whether an intervention designed to enhance CÉGEP students' formal reasoning increases their formal reasoning and performance; and
4) To explore different methodologies used to assess students' conceptual structures and to develop (or select) an efficient, reliable, and valid measure of students' conceptual structures.

LITERATURE REVIEW

2.1. Formal Reasoning

Piaget's theory of cognitive development consists of two sets of ideas: a set of ideas concerning knowledge, and a set of ideas concerning reasoning (Lunzer, 1986). The central idea within the knowledge set is that of *schemes.* Piaget considered schemes to be a learner's mental representation of previous experiences which determine the learner's interpretation, perception, and response to new stimuli. The totality of schemes denotes the learner's world view. In this research report, we have used the term *conceptual structure* rather than *scheme.* Piaget believed that schemes are dynamic structures that are constantly changing as a result of assimilation and accommodation. That is, when a stimulus evokes two conflicting schemes, equilibration occurs whereby the learner constructs a new more comprehensive scheme by the mutual accommodation of the two schemes "without actually destroying the original pair" (Lunzer, 1986, p 279). However, people prefer to assimilate new information rather than accommodate to new information, since the latter takes more effort. Only when the discrepancies are large enough, are learners aware (but often resistant to) the need for radical conceptual change. Thus, learners may simultaneously hold both naive and sophisticated concepts, and under the stress of being expected to function at a higher cognitive level than they are capable of, resort to the more familiar naive concept. These ideas are also expressed in the conceptual change literature by Vosniadou (1994), Vosniadou and Brewer (1994), and Jacobson and Archodidou (2000) who recorded the presence of these intermediate mental model, therein called synthetic models.

The central idea within the reasoning set is that of *structures*, which Piaget adapted from mathematical set theory. For example, four operations, labelled I (identity), N (negation), R (reciprocity), and C (correlative), can be used to convert one hypothesis to another. Piaget theorized that the set of these four operations constituted a structure of reasoning which learners acquired between the ages of 11 and 15. In this research report, we use the term formal reasoning to describe the acquisition of this INRC structure. Although this structure is described in terms of logical operations, these mental operations are also used to manipulate ideas in psychology, French and English grammar, physics, and other domains.

Inhelder and Piaget (1958) held that the acquisition of the INRC structure was required for the following nine reasoning skills:

- hypothetical reasoning: reasoning about possible outcomes (predicting).
- deductive reasoning: reasoning from general rule to specific instance.
- proportional reasoning: reasoning about relationships in form $x/y = a/b$.
- combinatorial reasoning: generating a list of all possible combinations of three or more variables.
- holding one variable constant: establishing a trial procedure to isolate the effects of one factor, exclude irrelevant factors, etc.
- correlational analysis: determining whether two events covary
- probabilistic reasoning: estimating the probability that a given event will occur.
- propositional, verbal, or symbolic reasoning: reasoning about relationships.
- complex problem solving: generalizations to a new context.

Characteristic errors are associated with the concrete level of functioning for each mental skill and are described by various authors (*e.g.*, Inhelder & Piaget, 1958; Kurfiss, 1983; Lawson, 1985). Five of the above formal reasoning skills have been identified as being essential for success in science and mathematics (Bitner, 1991). These are proportional reasoning, controlling variables, probabilistic reasoning, correlational reasoning, and combinatorial reasoning.

A number of pencil-paper tests of formal reasoning have been developed . For example, the Longeot test was constructed in French (Longeot, 1962) and consists of 28 items assessing class inclusion, propositional reasoning, proportional reasoning, and combinatorial analysis. This test was used (at least in part) by Torkia-Lagacé (1981) in a study of the formal reasoning level of more than 5000 students registered in French CÉGEPs. The Test of Formal Reasoning (TOFR) constructed by Lawson (1978) contains fifteen items assessing identifying and controlling variables, combinatorial reasoning, probabilistic reasoning, and proportional reasoning. The Test of Logical Thinking (TOLT) developed by Tobin and Capie (1981) includes ten items assessing identifying and controlling variables, combinatorial reasoning, probabilistic reasoning, proportional reasoning, and correlational reasoning. Finally, the Arlin Test of Formal Reasoning (ATFR) used in this study was constructed by Patricia Arlin (1982, 1984), and includes 32-items measuring eight reasoning skills. It has been extensively used in both cognitive and educational and is published by Slosson Educational Publications, Inc.

According to Inhelder and Piaget (1958) the approximate age at which students develop formal reasoning is between 11 and 15 years of age. However, many studies indicate that the majority of college students may only be functioning at the concrete level. For example, in a study of 14,000 representative British adolescents, Shayer and Wylam (1978) showed that no more than 30% develop even low levels of formal reasoning by age 16. Similar results were found in a replicate study carried out in Finland (Hautamaki, 1984). Research in the United States has also shown that university students are "transitional", *i.e.*, they reason formally only in limited areas abilities (Berenson, Carter, & Norwood, 1992; Lawson, 1992; McKinnon & Renner, 1971; Reyes & Capsel, 1986). In one study, 50% of university freshman were still reasoning at the concrete level on questions involving density in physics (Kurfiss, 1983).

Torkia-Laglacé (1981), in a study involving more than 5000 students from ten French CÉGEPs, found that while 69.1% of Pure and Applied Science students and 55.3% of Health students were functioning at least at the low formal reasoning level, only 38.2% and 26.8% of the Physical and Health technology students, respectively, were functioning at the same reasoning level. This survey of formal reasoning levels should also be carried out at English CÉGEPs. It has important implications for curriculum design and student support. If some students are "developmentally cognitively delayed" and colleges wish to reduce the failure or drop-out rate, the colleges must either change their admission practices, change the curriculum and/or pedagogy, or provide interventions accelerating students' cognitive development.

Recently, a theoretical model of formal reasoning development has been formulated and validated (Eckstein & Shamesh, 1992). Using this model, the time that it takes for half the population to move from the concrete to the formal operational level was determined. Most of the formal operations could be fitted with the identical curve supporting the contention that the various skills in formal reasoning appear simultaneously. Shayer and Wylam (1978) demonstrated that it takes 2.5 years for half the population to move from low concrete to high concrete and 7.8 years to move from high concrete to formal reasoning levels. Research has also been carried out demonstrating differences in the *rate* of development in different groups. Eckstein and Shamesh (1993) demonstrated that while it takes 6.36 years for half the boys to move from a concrete to a formal stage in their understanding of projectile motion on earth, it takes 10.7 years for half the girls.

Many studies have shown differences in the levels of formal reasoning between male and female students (Flexer & Roberge, 1983; Torkia-Laglacé, 1981; Lim, 1993), between students in different programs (Torkia-Laglacé, 1981) and between students belonging to different socio-cultural groups (Lawson & Bealer, 1984; Logan & O'Hearn, 1982). Researchers (Shayer & Adey ;Epstein 1974, 1977) have suggested that there are critical periods of brain growth. One such period is puberty during which the body is flooded with sex hormones and (maybe coincidently) the period of maximum rate of development of concrete and formal operational thinking. The brain growth that occurs at this time is primarily the production of more complex dendrite structures and is not associated to any specific functions. Epstein (2001) suggests that experience and instruction are necessary to produce the changes in cognitive function described by Piaget. Thus, differences in hormonal environments may explain gender differences during puberty. Since girls begin puberty earlier, their rate of development and not their final attainment may differ from boys.

One of the goals of the CÉGEP system is to give all Quebec students, regardless of their socio-cultural background equal opportunities for further education. If success in science courses requires formal reasoning skills which are not promoted in some socio-cultural environments, the CÉGEP system can only fulfill its mandate by providing some form of intervention.

2.2. Conceptual Structures.

Although most researchers agree on the active nature of learning, they differ on their underlying models of memory and learning. Broadly speaking, there are two categories of models of memory and learning: representational and social-neural. Although both postulate the active construction of conceptual structures, the two models differ fundamentally in the nature of conceptual structures, their assessment, and the implications to instructional design.

2.2.1. Representational Models of Learning and Memory

Traditional constructivist theorists (Ausubel, 1963; 1968; Novak, 1988; Piaget, 1954) hold a representational model of memory in which domain-specific declarative knowledge is stored as a network in long term memory (e.g., Anderson, 1983). These network models assume that concepts are stored as nodes interconnecting to form a vast associative network. Most researchers believe that the nodes are organized hierarchically such that more general concepts are supra-ordinate and more specific concepts are subordinate. In associative models, the links are unlabelled and therefore the same. On the other hand, propositional network models (Anderson & Bower, 1973; Anderson, 1983) hold that propositions rather than unitary concepts (*e.g.*, water) form the nodes. The links are labelled and therefore are not the same.

However, understanding science involves not only knowing *what* (declarative knowledge) but also knowing *how* (procedural knowledge). Therefore, representational models propose that procedural rules on how to manipulate the nodes are also stored (Anderson, 1983). Procedural rules for general situations are stored as schemata (Rumelhart, 1980) while procedural rules for specific subject matter domains are stored as mental models (Johnson-Laird, 1983; *cf* Gentner & Stevens, 1983). Mental models are mental analogies of the events along with procedural rules to mentally manipulate the event or situation. Individuals can use these models to predict future events, answer comprehension questions, or solve problems. Initially individuals construct conceptual structures that include only declarative knowledge; however, under appropriate conditions, learners downplay these semantic features and construct mental models of the situation, by encoding procedures, goals, and relationships (McNamara, Miller, & Bransford, 1991). Whether a learner opts to encode text propositionally or construct a mental model appears to be a function of text features, task difficulty, expertise, and knowledge of subsequent testing procedures (McNamara, Miller, & Bransford, 1991).

Most researchers, in the area of meaningful learning, consider that the conceptual structures held by learners determine subsequent learning (Ausubel, 1963; Roth, 1990; Bransford, Vye, Kinzer, & Risko, 1990). Meaningful learning occurs both by assimilation (the incorporation of new concepts into existing networks) and accommodation (the disassembly, re-examination, and rearrangement of the network to harmonize it with new concepts). Thus, when students are presented with new information, they must attend to the new information, construct some representation of the information in working memory, recall existing representations of prior knowledge (conceptual structures) from long-term memory, and consider the relational meaning of the new information relative to the existing conceptual structures. They subsequently incorporate the new information into a new conceptual structure by subsuming it under more inclusive concepts and/or by reorganizing the conceptual structure and communicate their conceptual understanding in some verbal form (Ausubel, 1963; Roth, 1990).

Most researchers also believe that learning or cognitive development is multidimensional (Anderson, 1982; deKleer & Brown, 1983; Glaser *et al.*, 1987; Royer, Cisero, & Carlo, 1993). For example, **Knowledge Acquisition** describes the degree to which learners acquire the declarative knowledge necessary to function within a specific domain. Although it is a prerequisite to meaningful learning, this dimension does not distinguish between novices and experts nor between meaningful learners and rote learners. **Knowledge Acquisition** can be (and usually is) assessed by traditional short-answer, true-false, multiple-choice tests. On the other hand, **Knowledge Organization** describes the manner in which knowledge is conceptualized, related, structured, and stored in long term memory. Novices, and presumably rote learners, store verbatim, unrelated and loosely structured information as opposed to experts, and presumably meaningful learners, who store highly interrelated and structured information.

2.2.1.1. Assessment of Conceptual Structures

Concepts are "cognitive devices for classifying objects in an economical way" Mashhadi, 1996, 5). However, a concept only has meaning to the degree that it is linked to other concepts (Ausbel, 1963; Klausmeier, 1990). A concept (*e.g.*, photosynthesis) includes the collection of memories (sensory, verbal, affective, *etc.*) that are associated with the label (*e.g.*, word, sign, etc.) and the pattern of its links to other concepts. Therefore, concepts are idiosyncratic and learning becomes the process whereby the learner expands, clarifies, organizes, and compares his or her associative network with that of an external standard (other learners, instructor, or "canon").

Conceptual structures are organized clusters of information stored in long-term memory (Klauseimer, 1990). Many conceptual structures have a hierarchical structure in which general superordinate concepts subsume specific subordinate concepts (Klauseimer, 1990). Since specific concepts are linked to general principles, learners can more easily apply their knowledge to novel problems. Thus, conceptual structures are derived representations of human memory based on associative or propositional networks specifying the set of concepts and the relationships among them. Research in conceptual structures began with Tulving (1962) who demonstrated that subjects order the items on a list according to the underlying relationships among the items. Many researchers have demonstrated that there are individual differences in the way that individuals structure knowledge (Koubek & Mountjoy, 1991, Chase & Simon, 1973).

Methods of inferring the way in which people organize domain-specific information is organized are very diverse (Egan & Schwartz, 1979; Adelson, 1981; Shoenfeld & Herrmann, 1982; Murphy & Wright, 1984). However, all are introspective, beginning with individuals making metacognitive judgments of what they know. These methods can be categorized as verbal reports, clustering methodologies, and scaling techniques (Koubek & Mountjoy, 1991). Each method involves, collecting the declarative knowledge that has been acquired, generating a representation of the conceptual structure, and quantifying the degree of conceptual organization.

2.2.1.1.1. Verbal Reports

Researchers elicit an individual's domain-specific knowledge by interviewing the subject, observing the individual completing a task (with or without interjections), analyzing written responses to an open-ended questionnaire, analyzing the subjects' explanations during task performance or subsequent to task performance (protocol analysis), or coding subjects' responses to multiple-choice questionnaires.

There are several problems with these methods of eliciting declarative knowledge. Firstly, naïve learners can often be inarticulate and thus produce sparse, incomplete and inconsistent verbal data. Secondly, these methods are highly subjective, with the researcher necessarily introducing his or her mental model of the domain either explicitly as the coding schema or implicitly in interpreting what the subjects know on the basis of their behaviour. Although, Ericsson and Simon (1984) maintain that if guidelines are followed, verbal reports can generate valid descriptions of what an individual knows about a specific topic, others argue that the process of interviewing students necessarily changes their conceptual structures by becoming an "inadvertent teaching instrument" (Demastes, Good, & Peebles, 1995, p 651). Finally, the elicited knowledge is static with procedural knowledge often being missed (Chi, Hutchinson, Robin, 1989).

Cognitive psychologists have developed several methods of generating representations of the way in which declarative knowledge is structured (Olson & Biolsi, 1991). For example, the subjects' verbal protocols can be parsed into propositions and the knowledge structure is represented as a network of labeled interconnected nodes. (d'Apollonia, De Simone, Dedic, Rosenfield, & Glashan, 1993; Frederiksen & Breuleux, 1990; Mosenthal & Kirsch, 1992). Other researchers have converted written or spoken text into concept maps. For example, Novak and Musonada (1991) interviewed students on their understanding of chemistry, converted their protocols into concept maps, and subsequently assessed the maps. Other researchers have coded subjects' performances on multiple choice tests into historical or developmental stages in the theoretical development of the domain (Chi, Feltovitch, & Glaser, 1981 ; Eckstein. & Shemesh, 1993; Vosniadou, & Brewer, 1994).

2.2.1.1.2. Clustering Methodologies

These methodologies are based on the premise that domain-specific knowledge is stored as clusters in long-term memory. These clusters are the building blocks from which more elaborate knowledge structures are constructed. Researchers generate the declarative knowledge in a domain by asking experts, teachers, or subjects to generate a list of concepts in the domain in question. Alternatively, they select the concepts from the syllabus or from chapter headings. However, Cooke and Macdonald (1986) found that different methods of obtaining lists elicited different types of information (general procedural rules versus declarative knowledge). Moreover, the selection of concepts at different levels of abstraction can cause problems in the subsequent representation of conceptual structures (Naveh-Benjamin, McKeachie, Lin, & Tucker, 1986).

Unlike the previously described methods, the subject, rather than the researcher, produces the representation of conceptual knowledge. Researchers have given subjects several tasks (e.g., card sorting (Hauslein, Good & Cummings, 1992), constructing an ordered list, and concept mapping) to generate their conceptual structures. For example, in the ordered-tree technique, an indirect measure of conceptual structure, subjects are presented with a list of researcher-generated key concepts and are asked to place them in an ordered list such that concepts having similar meanings are adjacent to each other. Subjects perform several trials (both cued and uncued) with an interval between each trial. A computer program is used to generate an ordered tree for each subject. This ordered tree is an indirect measure of each subject's cognitive structure and furnishes four measures, the degree of organization, the depth of hierarchical organization, the logical sequence, and the similarity to any other ordered tree.

Other researchers have asked subjects to construct concept maps in which they explicitly indicate the relationships among the concepts (Edmonson & Smith, 1995; Novak & Musonada, 1991; Ruiz-Primo & Shavelson, 1996, Wilson, 1998). However, there are many different methods of eliciting students' concept maps (e.g., "construct a map from scratch", "fill-in-the-map")and different scoring systems (e.g., counting links, nodes, and clusters, evaluating the accuracy of propositions). Ruiz-Primo and Shavelson (1996) concluded that there are reliability and validity problems with using concept maps to assess students' conceptual structures different methods of knowledge elicitation, different task demands, and different scoring techniques produce different knowledge representations as well as scores.

2.2.1.1.3. Scaling Methodologies

The derivation of conceptual structures involves the elicitation of a list of concepts (as discussed above), the elicitation of the relationships among the concepts (usually degree of relatedness, and the submission of this data to a scaling algorithm to produce a pictorial representation and various scores (coherence, similarity to other maps, etc.). Concepts and relationships can be elicitated by pairwise similarity ratings such as Pathfinder (Schaneveldt, 1990), Reportory Grid (Olson & Reuter, 1987), Twenty-Questions (Gammack, 1990), Sequential-Proximity Measures (Reitman & Reuter, 1980). In all cases the data can be converted to similarity matrices which are produce pictorial representations using graph theory to produce general weighted networks such as Pfnets by Pathfinder (Schaneveldt, 1990) or by multidimensional scaling. For example, researchers select terms within a given domain and ask subjects to rate the similarity between all pairs of items. Proximity matrices are generated and the Pathfinder algorithm generates networks in which the links may be either directed or non-directed. The algorithm also generates several measures of coherence and network similarity. General weighted networks are comparable to concept maps and although their equivalency has not been examined mathematically, it is possible to generate proximity matrices from ordered trees and concept maps and analyze them using these scaling algorithms (Wilson, 1998). Shavelson and his colleagues (Shavelson, Ruiz-Primo, & Wiley, 2004) have also used and written extensively on their use of a scaling technique to garner evidence of students' declarative knowledge. They use the term "cognitive maps" to describe the student's knowledge structure derived from similarity ratings (Wiley, 1998;

Schau & Mattern, 1997) to distinguish theses indirect methods from concept maps. We will also use this term in this report.

2.2.1.1.4. Summary of Assessment Methodologies

Several methods of generating and analyzing conceptual structures have been developed and analyzed. They are all based on rrepresentational models of memory. They all maintain that conceptual structures are symbolic internal representations of external reality stored in long-term memory. They are based on strong assumptions that conceptual structures are relatively stable (once learned), are meaningful (have semantic properties), and can be inferred from an individual's overt behaviour.

2.2.2. Socio-Neural (Non-Representational) Models of Learning and Memory

However, there are several models of learning and memory that maintain that conceptual structures are <u>not</u> stored in long-term memory; rather they are created *as needed* in working-memory. For example, PDP or connectionist models propose that knowledge is stored in the strengths of the "neural pathways" that are active during thinking (processing). When learning occurs, the input activates some neural pathways while either having no effect on other pathways or weakening others. Thus, knowledge is stored as the pattern of connections that are activated in a neural pathway (Churchland & Sejnowski, 1990). According to other non-symbolic models, knowledge is created dynamically as a by-product of interaction with the social and physical environment (Clancy, 1991; Smoliar, 1989). According to this view, memory is the ability to categorize sensory inputs (perceptions) and not the storage of features and attributes in a list. Representations of memory are then externalized as needed by any expression such as physical gestures, writing, or talking to oneself or others.

We have briefly (and inadequately) presented non-representational models of memory and cognition here because they make radically different assumptions about conceptual structures. For example, conceptual structures are not-symbolic representations, but rather patterns of neuronal activation. During social interactions (to oneself by self-talk or to others) these patterns of activation are externalized in short term memory. Conceptual structures are dynamic rather than stable. Conceptual structures have an abstract rather than literal meaning. Conceptual structures can only be inferred in social interactions. These two different models of memory and learning also have an impact on how we view the conceptual change literature, described below.

2.3. Conceptual Change

Many studies in science education, have shown that science concepts are difficult to understand at a deeper level. For example, students have persistent misconceptions about the processes of evolution (Ferrari & Chi, 1998; Jacobson & Archodidou, 2000), chemical equilibrium (Coll & Treagust, 2002; Suits, 2000) and diffusion/osmosis (Odom, 1995; Sanger, Brecheisen, & Hynek, 2001). These and other misconceptions have been shown to be highly resistant to instruction (e.g., Pfundt & Duit, 2003; Ram, Nersessian & Keil, 1997). These results have lead to theories of how these misunderstood concepts develop and what the process of change may involve.

Piaget (Inhelder & Piaget, 1958) proposed that the changes in children's conceptions of the world, from naive to scientific views arise as a result of developmental stages resulting from the acquisition of formal reasoning structures (INRC). Thus, as a result of biological maturation, learners acquire **domain-independent** skills that allow them to reconstruct their conceptual structures by a process of assimilation and accommodation. According to Piaget, this restructuring will happen when learners are confronted with anomalous information or experience. Rumelhart and Norman (1981) suggested that as learners mature in their understanding of a topic, they progress through an initial *accretion* stage (the acquisition of new-information by its addition to pre-existing conceptual structures), an intermediate *tuning* stage (the slow modification of conceptual structures), to a final *restructuring* phase (the construction of new schemata by the subsumption of surface features by general principles.

Posner, Strike, Hewson, and Gertzog (1982) proposed the first model of conceptual change relevant to science education. They proposed that students change their conceptions when

- they become dissatisfied with their conception;
- they are confronted with an alternative intelligible conception;
- the new conception is plausible; and
- the new conception is fruitful.

They (Strike & Posner, 1985; 1992) later extended their model and proposed that misconceptions are not the product of clearly articulated beliefs; but rather, artifacts of deeply entrenched problems in the conceptual 'ecology'. That is, misconceptions are weakly developed and incomplete conceptual structures that are unstable. Conceptual change then would involve the replacement or introduction of concepts to produce more stable structures. Strike and Posner (1992), Pintrich, Marx, and Boyle (1993) and many other researchers have extended this model of conceptual change to include the influence of affective and motivational factors.

Conceptual change models fall into two primary groups (Charles, 2003; Nersessian, 1989), the more conventional view known as an accommodation model, posited by Piaget, and elaborated on by Strike and Posner (1985, 1992) consider the conceptual ecology of the learner but assert that, through reason, the more fruitful explanation will be adopted. The other camp takes a more structural approach, positing that it is the very nature of the explanation, the underlying beliefs of causation that need to be addressed. Within these models are: (1) Vosniadou's "framework theories" (e.g., Vosniadou & Brewer, 1994), (2) diSessa's "causal net" (diSessa & Sherin, 1998), and (3) Chi's "ontological beliefs" (Chi et al. 1994). Although these researchers disagree on several fundamental points related to how coherent or fragmented these naïve "theories" or beliefs are, they agree that these beliefs need to be altered in order to repair and/or remove misconceptions.

The former (accommodation models) implicitly hold a representational model of learning and memory since they define conceptual changes as the replacement or addition of declarative knowledge nodes. They differ from more recent (restructuring models) in which the emphasis has shifted to the restructuring of underlying "structures" or "mechanisms". There are fundamental differences between theorists who propose restructuring models of conceptual change. For instances, diSessa and Sherin (1998) propose that naïve learners possess impoverished causal models for understanding physics concepts, which are organized as fragmented *phenomenological primitives* (p-prims) or "knowledge in pieces". On the other hand, Vosniadou and colleagues (Vosniadou and Brewer, 1994; Vosniadou and Ioannides, 1998) suggest that instructionally based conceptual change is difficult because existing naïve "*framework theories*" (derived from the learner's ontological and epistemological presuppositions) are coherent systems of explanations that are grounded in everyday experiences and years of confirmation. Then there are theorists such as Chi and her colleagues (Chi, 1993; Chi, 2000; Chi, in press; Chi & Roscoe, 2002; Chi et al., 1994; Slotta & Chi, 1999) who define conceptual change as *ontological reassignment* of preexisting conception. They hypothesize that novices, unlike experts, assign concepts to ontological categories that are unable to support explanations of the phenomena, thereby acquiring robust misconceptions and flawed knowledge acquisition.

From the "accommodation" perspective, students' conceptual structures can be collected by any of the methods described above. However, from the "restructuring" perspective, students' underlying explanatory frameworks must be collected. This is usually accomplished by coding student interviews or problem solutions. For example, Eckstein and Shemesh (1992, 1993) coded students' responses to four physics problems and identified their underlying formal reasoning stage. Vosniadou and Brewer (1994) coded students' work and demonstrated that there are developmentally distinct stages in conceptual change: (a) initial mental model, (b) synthetic mental model – learner attempts to reconcile the science model with initial model, and (c) scientific mental model. Jacobson and Archodidou (2000) coded students' responses to questions on evolution on the basis of their treatment of four evolutionary concepts and identified three developmental stages (novice, synthetic, and expert). d'Apollonia, Charles, and Boyd (2004), using Jacobson and Archodidou's coding scheme, showed that students' cognitive maps and essays, reflected students' underlying understanding of complex systems. Thus, these studies illustrate that it is possible to demonstrate the restructuring of underlying explanatory frameworks as well as domain-specific conceptual structures.

2.3. Motivational Factors

Some researchers (Strike & Posner, 1992; Pintrich, Marx, & Boyle, 1993) have criticized conceptual change models that do not consider motivational and affective factors (cold conceptual models). Pintrich et al. noted that since 1962 there has been agreement that the process of scientific research is itself affected by psychological, sociological, and cultural influences. Researchers have shown that the nature of learning (Eylon & Linn, 1988), motivation (Dweck & Leggett, 1988), affect (McCombs & Whisler, 1989), self-efficacy (Harter, 1986), and meta-cognition (Weinstein, Zimmermann, & Palmer, 1988) influence conceptual change. Researchers have also indicated that cognition does not occur independent of attributions (Weiner, 1985), perceptions of competence and personal control. For example, self-efficacy influences students' choice of tasks, engagement, and persistence (Harter, 1986). Control beliefs guide students' use of strategies and guide their response to new dissonant information. Self-efficacy, affect, and control beliefs affect information processing in that they determine whether students attend to new information, whether they activate their general knowledge to evaluate this new information, and whether they engage in elaboration or restructuring of their mental models.

Attributional retraining is a therapeutic intervention that attempts to change students' explanations about their success and failure. Perry and his colleagues (Perry & Penner, 1990; Menec & Perry, 1995; Perry, Hall, & Ruthig, 2004) have shown that it can enhance student motivation and academic achievement, especially with students who are at high risk because of maladaptive attributions to ability.

2.4. Main Research Questions

Thus, we had several goals in conducting this research.

- Firstly, we wanted to know what were the formal reasoning skills of CÉGEP students taking science courses. Were there any systematic differences in their formal reasoning skills due to age, gender, and or Program of Study?
- Secondly, we wanted to know whether an intervention incorporating attributional retraining and exercises in formal reasoning would enhance student performance.
- Thirdly, we wanted to explore different methods of assessing students' conceptual structures and design a methodology to be used in subsequent research.

METHODS

3.1 Research Design

We addressed the following questions over three studies conducted over four semesters. In **Study 1,** employing a survey research design, we addressed two questions "*What formal reasoning skills do CÉGEP science students have?*" and *What are the relationships among motivational factors, achievement, and formal reasoning?* In **Study 2,** employing a Posttest-Only Design with Nonequivalent Comparison Groups Design, we addressed the question "*Does an intervention designed to improve students' formal reasoning and attributions enhance student performance?*". In Study 3, employing a mixed methods case study design, we addressed the question " *Can we measure changes in students' conceptual structures?*".

3.1.1. Participants

In **Study 1**, the subjects were 525 college science students registered in pre-university and technology programs taking Chemistry NYA (formerly 201). However, only 511 students signed the informed consent form. The students' average age was 19.4 years and the population included 252 males and 258 female. While 53.4% of the students spoke English as their mother tongue, 31.3% and 15.3% spoke French and other languages, respectively.

In **Study 2**, the subjects were 124 college science students registered in the pre-university program taking Biology NYA (formerly 301). The students were in 4 classes, the average age was 20.1 years. Intact classes were selected as experimental and control groups. There were 67 (29 male and 38 female) students in the experimental group and 57 (24 male and 33 female) students in the control group.

In **Study 3**, the subjects were 31 college science students who volunteered (for a token stipend) to participate in the study. They came from different science backgrounds.

3.1.2 Instructional Intervention

In **Study 1**, students were asked to complete a questionnaire consisting of 12 items measuring Academic Self-Efficacy, Self-Concept, and Perceived Academic Control, 3 items measuring demographic variables, and the 32 items from the Arlin Test of Formal Reasoning (ATFR) in their Chemistry classes. The questionnaire is presented in Appendix 1 and is described below.

In **Study 2,** 4 intact classes of 124 students were assigned to experimental and control conditions. The experimental classes viewed an attribution training tape provided by Dr. Ray Perry (Struthers & Perry, 1996) and then worked in small groups discussing the implications of the tape to their success in the course. They were asked to come up with concrete suggestions on "controlling their learning". The control group viewed a tape on "note taking" and then worked in small groups discussing the video. Two laboratory exercises were developed; the experimental intervention included materials from CASE (Adey, Shayer & Yates, 1989) explicitly teaching proportional reasoning, and combinatorial reasoning (See Appendix 2). The control group was given the same exercises but excluding the training in formal reasoning.

One week after the intervention, both groups of students completed the abbreviated questionnaire from Study 1 (consisting of the 16 questions assessing Correlations, Combinations, Proportionality, and Probability). Six weeks after the intervention, students took a lab test in which they were asked the same question on calculating the size of an object as seen under a microscope (See below). At the end of the course they were asked the same questions on evolution (See Appendix 3).

In **Study 3,** 31 students met with a research assistant for between one and a half and two hours and completed four tasks. Firstly, they completed a multiple-choice test which included 24 questions on the chemical properties of water and 24 questions on the biological characteristics of osmosis and diffusion derived from the literature on misconceptions (Griffith & Preston, 1992 and Odom & Barrow, 1995, respectively). The test is included in the Appendix 3.

Secondly, they rated the degree of relatedness among all pairs of terms in each of the sets described below.

- Atoms, Covalent bonds, Electrons, Gaseous phase, Hydrogen, Hydrogen bonds, Liquid phase, Molecular shape, Molecular size, Molecules, Negative charge, Oxygen, Polar bonds, Positive charge, Solid phase, Water.

- Concentration Gradient Energy, Hypo-Osmotic, Membrane, Osmosis, Particles, Water, Diffusion, Hyper-Osmotic, Iso-Osmotic, Molecules, Passive Transport, Solvent

Thirdly, they wrote the following two essays:

- *Describe the chemical properties of water. Include the following terms in your essay: atoms, covalent bonds, electrons, gaseous phase, hydrogen, hydrogen bonds, liquid phase, molecular shape, molecular size, molecules, negative charge, oxygen, polar bonds, positive charge, solid phase, water.*
- *Explain the process of osmosis and diffusion in living cells. Include the following terms in your essay: concentration gradient, energy, hypo-osmotic, membrane, osmosis, particles, water, diffusion, hyper-osmotic, iso-osmotic, molecules, passive transport, solvent*

3.1.3. Measures and Data Analysis

3.1.3.1. Formal Reasoning (Used in Study 1 and Study 2)

The **Arlin Test of Formal Reading (ATFR)** is a 32 item pencil and paper test developed by Patricia Arlin (Arlin, 198, 1984) to assess students' ability to complete the tasks employed by Inhelder and Piaget (1958). That is, they were designed to assess students' reasoning about the following eight concepts:

- Multiplicative compensations,
- Correlations,
- Probability,
- Combinations,
- Proportions,
- Forms of conservation beyond direct verification,
- Mechanical equilibrium, and
- The coordination of multiple frames of reference.

Thus, the test can be used to score students overall formal reasoning performance, their overall cognitive level or developmental stage (Low Concrete, High Concrete, Transitional, Low Formal, and High Formal). The reliability of the total test, as determined by Cronbach's Alphas, were between 0.60 and 0.73, depending on the age of the students. Test-retest reliabilities were found to be between 0.76 and 0.89. The definitions of each stage are presented in Table 1.

Table 1. Definitions, and Descriptions of Stages of Formal Reasoning (Arlin, 1982, 1984).

Stage	Definition	Description
Low Concrete	Between 0 and 7 on total test	Students demonstrate no evidence for reasoning at the abstract level and demonstrate difficulties at problem solving.
High Concrete	Between 8 and 14 on total test	Students demonstrate some evidence for systematic problem solving, but no evidence of generalizing schemas or abstractions to other similar problems. Although students' provide evidence of ability to categorize, they demonstrate poor abilities at inference.
Transitional	Between 15 and 17 on total test	Although these students demonstrate some evidence for both generalizations and inferences, they are inconsistent. Thus, it is difficult to determine whether these students are functioning at the high concrete or low formal without examining their subscores.
Low Formal	Between 18 and 24 on total test	Students provide evidence of both generating abstract schemas and making inferences. They demonstrate the consistent use of 3 to 5 of the eight subskills. However, they still require scaffolding to perform adequately for the remaining subskills.
High Formal	Between 25 and 32 on total test	Students demonstrate that they have acquired all eight formal reasoning subskills although they may need some reinforcement.

The ATFR can also be used to score students' performance on the eight sub-skills described in Table 2.

Table 2. Description of Formal Reasoning Sub-skills (Arlin, 1982, 1984).

Formal Schema	Description	Example of Tasks
Multiplicative Compensations	Reasoning about effects of two or more variables which have an inverse relationship. That is gains or losses in one variable are compensated by gains or losses in the other .	computing the effects of changes of pressure, temperature, or volume on gases analyzing closed systems in economics, or social science.
Correlations	Reasoning whether two events are or are not related and if they are, about the strength of the relationship.	determining the influence of fertilizer concentration on plant growth; determining the influence of wars on the world price of gas
Probability	Reasoning about the likelihood that one or more events will happen.	determining the chance that an observed difference in heart rate is due to chance, determining that a specific political outcome will occur given several scenarios
Combinations	Reasoning that generates all possible combinations of a given number of variables.	determining all possible color combinations s in art determining all possible genotypes in genetics
Proportions	Reasoning about the equality of two ratios which are proportionally related.	drawing maps or diagrams to scale in art and biology interpreting analogies and complex poetic examples
Forms of conservation beyond direct verification,	Reasoning about the influence of one variable on a second which is not directly observable but must be inferred. There are many phenomena which we cannot observe directly.	questions about momentum which no one has seen questions about genes or alleles reading comprehension requiring the making of inferences

Table 2 cont. Description of Formal Reasoning Sub-skills (Arlin, 1982, 1984).

Formal Schema	Description	Example of Tasks
Mechanical equilibrium	Reasoning about the influence of many coordinated variables simultaneously that affect equilibrium processes.	questions in hydraulics, piston and similar types of problems questions in economics pre presupposing equilibrium in the system. the interpretation of complex plots in plays
The coordination of multiple frames of reference	Reasoning about the coordination of two related systems, each involving a direct and an inverse operation. It represents a type of relativity of thought.	any task that requires analyzing complex systems across different levels or time frames analyzing the influence of local decisions (family voting patterns) on global outcomes (world trade).

3.1.3.2. Motivational Factors (Used in Study 1 and Study 2)

A 12-item instrument was developed consisting of 12 questions measuring **Academic Self-Efficacy, Academic Self-Concept,** and **Perceived Academic Control.** The questions are presented in Table 3 along with a reliability estimated determined on 429 student responses using SPSS Reliability Analysis.

Table 3. Items used to assess **Academic Self-Efficacy, Academic Self-Concept**, and **Perceived Academic Control.**

Test Item	Factor	CA
I am a failure academically	Academic Self-Efficacy	
I am able to do things relatively well	Academic Self-Efficacy	
I am satisfied with myself as student	Academic Self-Efficacy	.58
I expect to do extremely well in science	Academic Self-Efficacy	
I have control over academic performance	Perceived Academic Control	
I have little control over academic performance	Perceived Academic Control	.62
I am responsible for my academic performance	Perceived Academic Control	
I have little control over grades	Perceived Academic Control	
I am a person of worth	Self-Concept	
I have a number of good qualities	Self-Concept	.62
I do not have much to be proud of	Self-Concept	
I have a positive attitude to myself	Self-Concept	

CA is Cronbach's Alpha

3.1.3.3. Achievement tests (Used in Studies 2 and 3)

The achievement tests used in this study are briefly described below and are given in Appendix 3.

3.1.3.3.1. Chemistry of Water

This test was constructed from the interviews conducted to determine the misconceptions held by grade 12 students in chemistry (Griffiths & Preston, 1990). It consisted of 24 items assessing the following misconceptions about the water molecule:

- Structure (Reliability estimate this study **Cronbach's α = 0.64**) ;
- Composition (Reliability estimate this study **Cronbach's α = 0.58**);
- Size (Reliability estimate this study **Cronbach's α = 0.67**);
- Shape (Reliability estimate this study **Cronbach's α = 0.09**);
- Weight (Reliability estimate this study **Cronbach's α = 0.78**); and,
- Energy (Reliability estimate this study **Cronbach's α = .46**).

Therefore, the test appears to have reliability characteristics for 4 misconceptions (**Structure, Composition, Size**, and **Weight**). Students' performance on each of the four reliable factors were computed and scored. If they scored between 0 and 25% they were considered to have no understanding of the concept; if they scored between 26 and 69% they were considered to be somewhat confused with the concept; if they scored above 70% they were considered to understand the concept.

3.1.3.3.2. Osmosis/Diffusion

This test described by Odom and Barrow (1995) was used in this study. It consisted of 24 items assessing the following misconceptions about osmosis/diffusion:

- Solutions (Reliability estimate this study **Cronbach's α = 0.64**) ;
- Tonicity (Reliability estimate this study **Cronbach's α = 0.40**);
- Diffusion (Reliability estimate this study **Cronbach's α = 0.74**);
- Osmosis (Reliability estimate this study **Cronbach's α = 0.76**).

Therefore, the test appears to have reliability characteristics for 3 misconceptions (**Solutions, Diffusion**, and **Osmosis**). Students' performance on each of the three reliable factors were computed and scored. If they scored between 0 and 25% they were considered to have no understanding of the concept; if they scored between 26 and 69% they were considered to be somewhat confused with the concept; if they scored above 70% they were considered to understand the concept.

3.1.3.3.3. Evolution

A common set of questions was developed by the biology faculty of Dawson College to assess students' understanding of evolution. They were adapted from Bishop and Anderson (1990). The test is included in Appendix 3. We subsequently also used the essay question from this test in a study on students' mental models of evolution (d'Apollonia, Charles, & Boyd, 2004).

3.1.3.3.4. Lab Question

A common lab question was developed by the Biology faculty to determine whether students understood the relationships among magnification, field diameter, light intensity, and observed and true size of an object as seen under the microscope. Students went to a microscope that was set at a magnification of (40x, 100x, or 400x). They viewed an organism under the microscope and had three minutes to answer the following question:

Observe the object under the microscope and given that the field diameter at a total magnification of 100x is 2 millimeters, estimate the size of the structure indicated by the pointer in micrometers. Show all your calculations.

The students' responses were graded on a scale of 5.

3.1.3.4. Similarity Ratings (Used in Study 3)

Students were asked to rate the similarity between all pairs of terms in the two lists of terms using the program "Rate" that is part of the PCKnot and MacKnot software from Interlinks, Inc. The ratings are converted into distances (or proximities) between all pairs of terms and translated mathematically into triangular matrices. The Pathfinder algorithm translates the matrix into a network representation in which the nodes represent concepts and the lines represent relationships between concepts. The PCKnot and MacKnot software were used to aggregate the students' similarity ratings to produce composite cognitive maps. The cognitive maps were analyzed qualitatively. That is, the cognitive maps were scanned to determined whether the node to node relationships made "sense".

3.1.3.5. Essays (Used in Study 3)

The students' essays were segmented into propositions. We subsequently coded each proposition (if relevant) on the basis of the student's understanding of the concepts associated with the misconceptions on the chemistry of water and osmosis presented in Table 4. We computed a total score for each test and subscores for each concept. The interraret reliabilities on 20% of the essays were between 57 and 85%.

Table 4. Coding Rubric Used for Essays on Chemistry of Water and Osmosis.

Essay	Concept	Examples of statements
Water	Structure	Molecules of water are polar. One molecule of water is attracted to another because water is polar. Oxygen portion of water has a negative charge. Hydrogen portion of water has a positive charge. Water can exist in the gaseous, liquid, or solid state.
	Composition	Water is composed of two hydrogen molecules and one oxygen molecule covalently bonded.
	Shape	The water molecule has a bent shape
	Shape	*Not coded because too few entries*
	Weight	*Not coded because too few entries*
Osmosis	Diffusion	Particles move down a concentration gradient Rate of diffusion is proportional to concentration difference. Diffusion does not require energy (Passive)
	Solutions	Water is the solvent
		Particles in solution are in constant random motion
	Osmosis	Osmosis if the movement of a solvent (i.e., water) across a semipermiable membrane.
		Osmosis does not require energy. (Passive)
		When a cell is placed in an iso-osmotic solution, water the cell and enter the cell in equal amounts.
		When a cell is placed in a hyper-osmotic solution, water will leave the cell and the cell will shrink.
		When a cell is placed in a hypo-osmotic solution, water will enter the cell and the cell will swell.
	Tonicity	An iso-osmotic solution has the same concentration of particles[1] and water molecules as that in a cell.
		A hypo-osmotic solution has a lower concentration of particles[1] and a higher concentration of water molecules than that in the cell.
		A hyper-osmotic solution has a higher concentration pf particles[1] and a lower concentration of **water molecules** than that in the cell.

[1] That do not diffuse through the membrane

RESULTS AND DISCUSSION

We addressed the following questions over three studies conducted over four semesters. In **Study 1** we addressed two questions "*What formal reasoning skills do CÉGEP science students have?*" and *What are the relationships among motivational factors, achievement, and formal reasoning?* In **Study 2** we addressed the question "*Does an intervention designed to improve students' formal reasoning and attributions enhance student performance?*". In **Study 3** we addressed the question " *Can we measure changes in students' conceptual structures?*". We will address the results of each question in turn, including the discussion related to the specific question.

4.1 Study 1

4.1.1. Question 1*: What formal reasoning skills do CÉGEP science students have?*

The average total score on the ATFR for the 511 students in Chemistry NYA was 19.8 with a standard deviation of 5.3. Male students (Mean = 20.8, SD = 5.3) scored significantly higher ($t = 4.17$, $df = 508$, $p = .000$) than did female students (Mean = 18.9, SD = 5.2). Figure 1 shows the distribution of total scores on the Arlin Test of Formal Reasoning (ATFR) for the 511 students in Chemistry NYA and indicates that the scores are normally distributed.

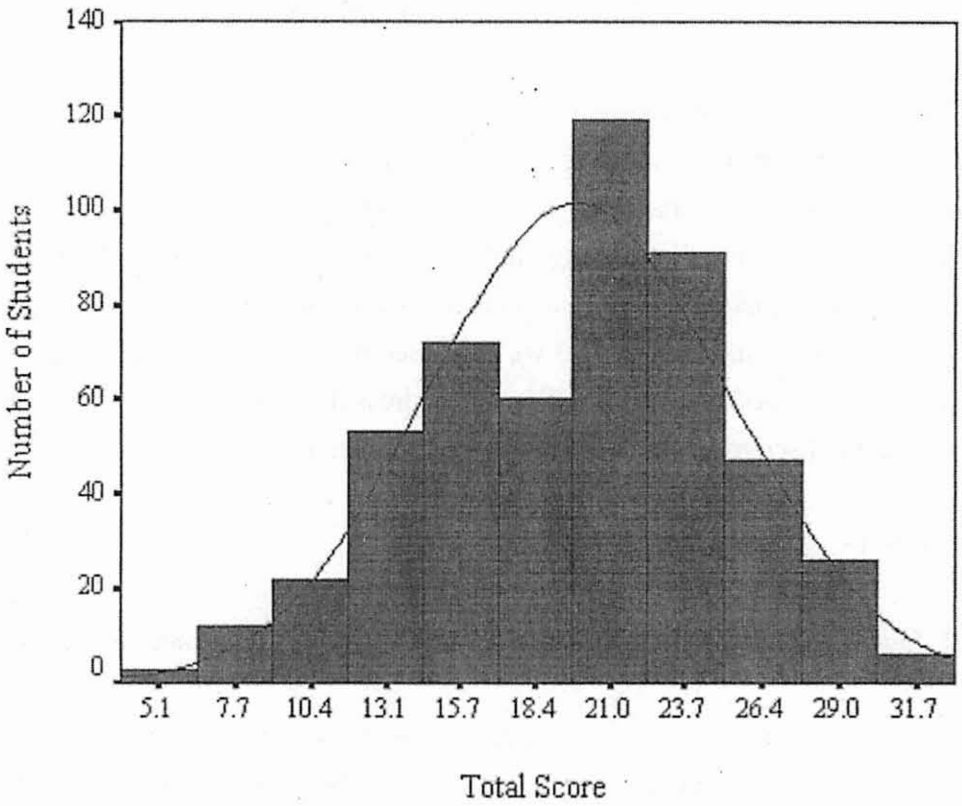


Figure 1. Distribution of formal reasoning for CÉGEP students in Chemistry NYA.

Table 5 shows the distribution of male and female students into the five levels of formal reasoning (low concrete, high concrete, transitional, low formal, high formal).

Table 5. Percentage of Male (258) and Female (252) Students at each Stage of Formal Reasoning Compared to the Norm Group (411).

Group	Low Concrete	High Concrete	Transitional	Low Formal	High Formal
Norm*	**5**	**23**	**13**	**39**	**20**
Males	0.8	14.3	11.6	46.1	27.1
Females	1.6	18.7	16.3	49.2	14.3

- The data for the norm group was taken from the test booklet (Arlin, P.(1992). *Arlin test of formal reasoning*. Slosson Educational Publications, Inc. New York) and was obtained from grade 12 students taken from 14 states in the United States of America and 3 provinces in Canada..

CÉGEP students are functioning at higher formal reasoning levels than the norm for their age group. There are fewer students functioning at concrete reasoning levels; however, significantly fewer female students than male students are functioning at the high formal level.

Although the total scores tell us a student's level of formal reasoning, it does not provide us with an understanding of his or her strengths and weaknesses. Table 6 illustrates the students' scores for each of the eight specific reasoning skills.

Table 6. Mean and Standard deviation for scores for male (258) and female (252) students on each sub-scale compared to those for the norm group (411).

Formal Reasoning Skill	Male Students		Female Students		Norm Group	
	Mean	SD	Mean	SD	Mean	SD
Multiplicative Compensation	2.74	1.34	2.23	1.35	2.97	1.04
Probability	3.31	0.92	3.05	1.06	3.07	1.07
Correlations	3.28	1.09	3.23	1.12	3.25	1.05
Combinations	1.83	1.15	1.92	1.16	1.41	1.30
Proportions	3.12	1.10	2.51	1.28	2.23	1.44
Conservation	1.56	1.20[2]	1.51	1.28	1.17	1.11
Mechanical Equilibrium	2.43	1.15	2.34	1.20	1.55	0.98
Multiple Frames	2.55	1.20	2.08	1.26	2.15	1.25

We carried out a multivariate analysis of variance to determine whether age and gender were significantly associated with formal reasoning. There was a significant association between formal reasoning and age ($F = 2.11$, $df = 8, 491$, $p < .002$), and between formal reasoning and gender ($F = 2.56$, $df = 8, 491$, $p < .001$). Univariate tests indicated that older students are significantly less skilled at reasoning about combinations, probability,

[2] all tests on multiple variables were carried out with the SPSS Multivariate General Linear Model

proportions and multiple frames (See Figures 2a, 2b, 2c, and 2d). combinations, proportions, and multiple frames.

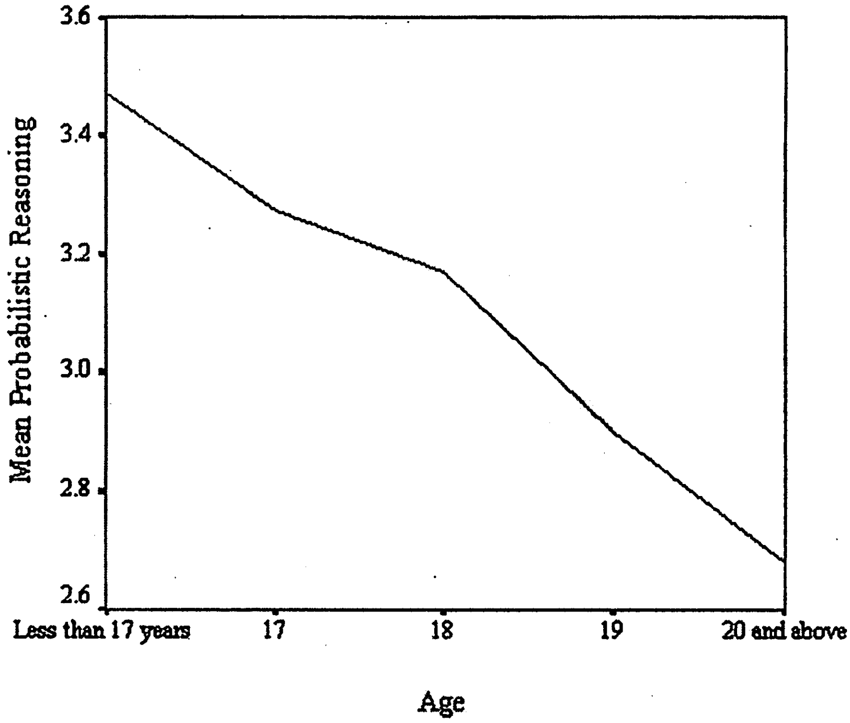


Figure 2a. Influence of age on reasoning about probability.

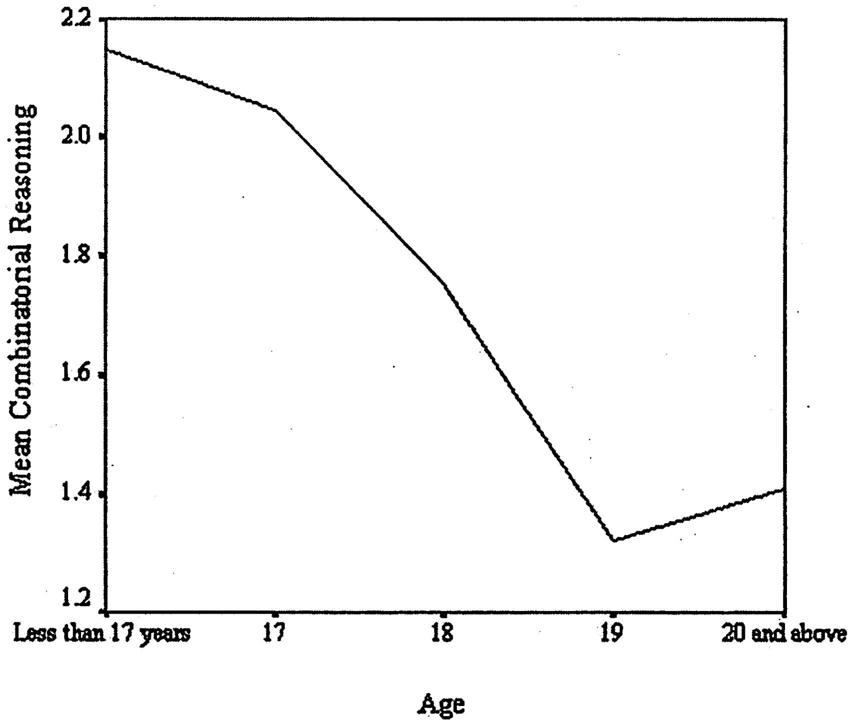


Figure 2b. Influence of age on reasoning about combinations.

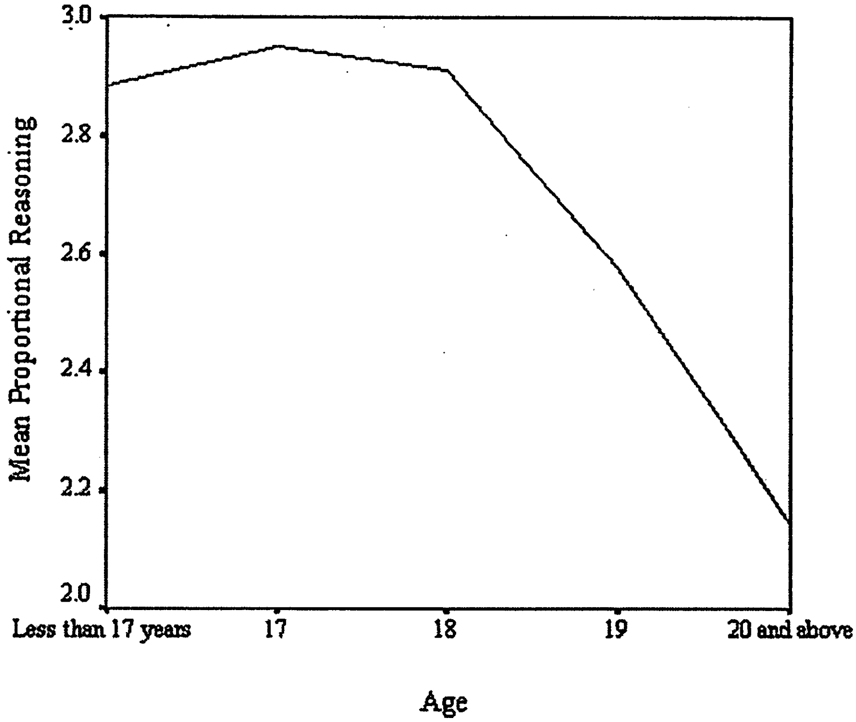


Figure 2c. Influence of age on reasoning about proportions

Figure 2d. Influence of age on reasoning with multiple frames

Univariate tests also indicated that gender was significantly associated with reasoning about combinations ($F = 7.92$, $df = 2$, $p < .045$) and proportions ($F = 14.71$, $df = 2$, $p < 005$). Table 7 shows that female students scored higher than male students on reasoning about combinations; however, males scored higher than females on reasoning about proportions.

Table 7. Scores of Male (258) and Female (252) Students on Reasoning about Combinations and Proportions.

Formal Reasoning Skill	Male Students		Female Students	
	Mean	Standard Error	Mean	Standard Error
Combinations	1.58	.10	1.85	.09
Proportions	2.92	.10	2.48	.09

The influence of age on formal reasoning was not only unexpected, it is contrary to the expected results. One possibility is that, students who have failed (and presumably less skilled) are older than other students. Also, students in some of the technological programs such as Nursing, may be older and possibly less skilled. To test this possibility, we reanalyzed the data set and tested the hypothesis that the formal reasoning skills of Pre-University Science students were significantly higher than those of Technology students. The results indicate that students in Pre-university Programs are significantly ($F = 9.63$, $df = 8, 395$, $p < .001$) more skilled at formal reasoning than are students in Technology Programs. Table 8 and Figure 3 show that more technology students are at concrete levels than science students.

Univariate tests indicate that technology students are less able than science students to reason about probability, correlations, combinations, proportions, conservation, mechanical equilibrium, and multiple frames.

Table 8. Percentage of Students in Pre-university (289)) and Technology (252) Programs Students at each Stage of Formal Reasoning.

Group	Low Concrete	High Concrete	Transitional	Low Formal	High Formal
Pre-University	1.0	10.4	11.8	48.8	28.0
Technology	1.7	31.3	18.3	45.2	3.5

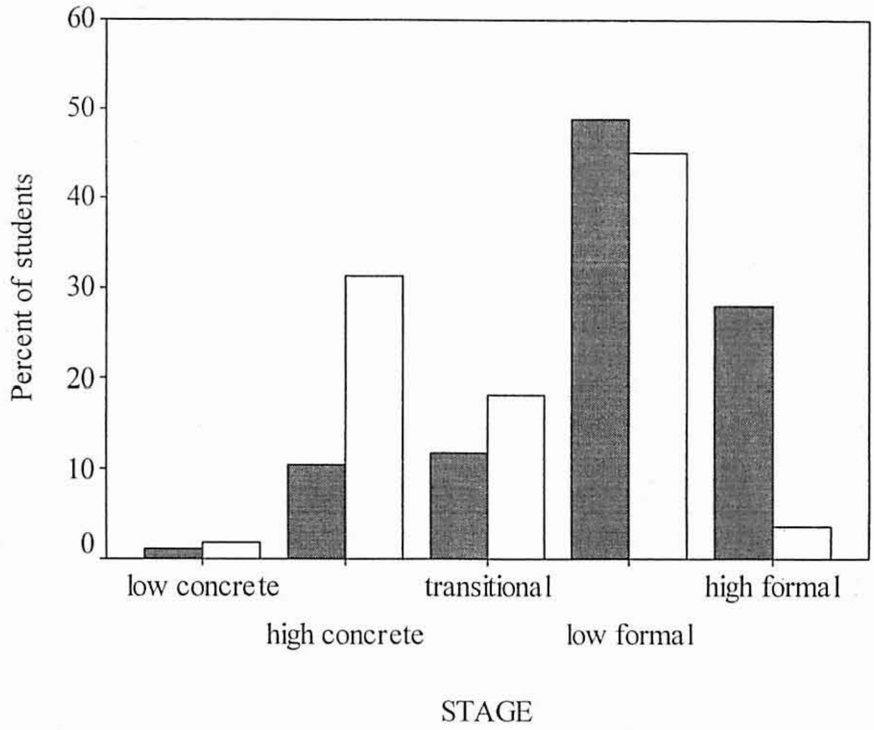


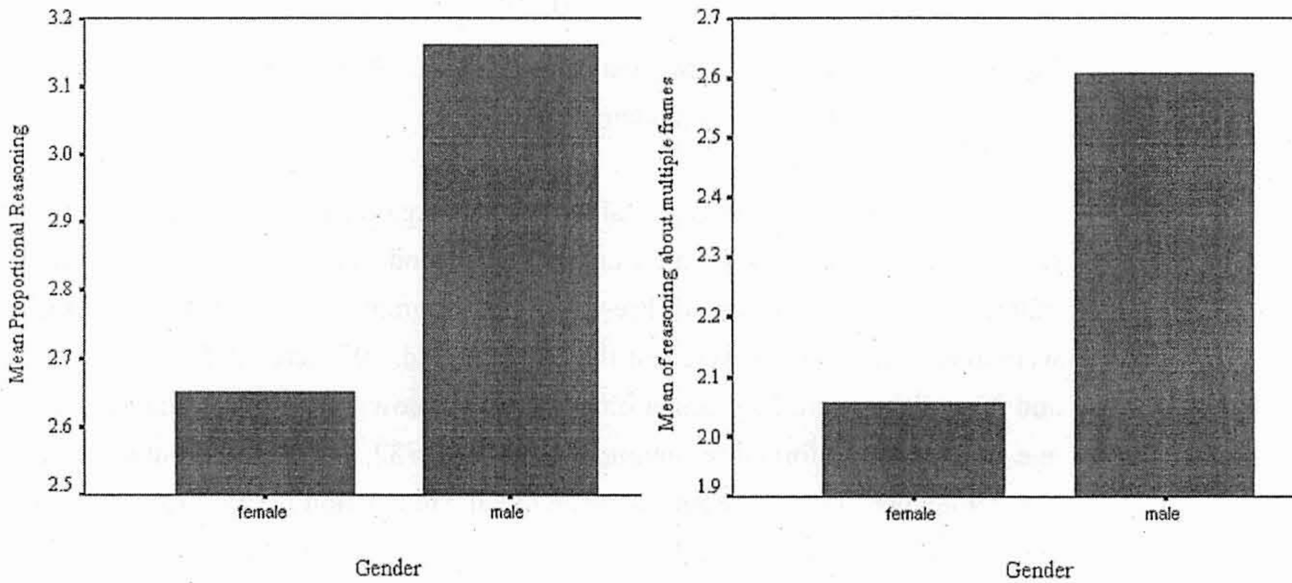
Figure 3. Distribution of formal reasoning for CÉGEP science students (filled bars) and technology students (clear bars).

To determine whether age affected formal reasoning independent of program of study, we reran the Multivariate General Linear Model analysis for the subset of students (N =205) who were in the Science Pre-university Program. Of these, 106 were female and 99 were male. Ten students were less than 17 years old, 107 were 17, 50 were 18, 16 were 19, and 22 students were 20 years or older. However, now there is a significant interaction of age and gender on formal reasoning ($F = 1.39$, $df = 32, 173$, $p < .05$) but no main effect of age nor gender. Univariate tests indicate that the interaction is significant only for reasoning about proportions ($F = 3.42$, $df = 4, 201$, $p < .01$) and multiple frames ($F = 3.21$, $df = 4, 201$, $p < .02$).

Table 9 shows the scores of all pre-university students. It indicates that while the average scores of these students are very similar to those of the norm group, there is a large decrease in the standard deviation. That is, the pre-university science students are a much more homogeneous group. However, as Figures 4a and 4b indicate, 17 year old male students are significantly better at reasoning about proportions and multiple frames than are 17 year old female students. However, there are no differences in the reasoning abilities on other formal reasoning tasks between male and female students at other ages.

Table 9. Mean and Standard deviation for scores for students (N = 205) in science pre-university program.

Formal Reasoning Skill	Science Students		Norm Group	
	Mean	SD	Mean	SD
Multiplicative Compensation	2.35	.16	2.97	1.04
Probability	3.10	.12	3.07	1.07
Correlations	3.18	.13	3.25	1.05
Combinations	1.71	.13	1.41	1.30
Proportions	2.72	.13	2.23	1.44
Conservation	1.52	.16	1.17	1.11
Mechanical Equilibrium	2.47	.14	1.55	0.98
Multiple Frames	2.10	,14	2.15	1.25



(a) (b)

Figure 5a and 5b. Reasoning about proportions and multiple frames in 17 year old female and male students.

4.1.2. Question 2: *What are the relationships among motivational factors, achievement, and formal reasoning?*

The correlations between formal reasoning (total score) and high school grades in math, the sciences, English, and Quebec history are presented in Table 10. All correlations are significant at an α level of .01. Furthermore, the students' English scores are highly correlated with their science grades (.54, .45, .55 and .57 for Biology, Chemistry, Physics, and Mathematics, respectively).

Table 10. Correlation between Formal Reasoning (total scores) and high school grades (average of all grades in discipline).

High School Course	Pearson product correlation	Sample size
Biology	.34*	106
Chemistry	.39*	370
Physics	.48*	426
Mathematics	.40*	428
Quebec History	.31*	443
English	.25*	338

Table 11 indicates that there is a significant correlation between Formal Reasoning (total score) and both Self-Concept and Perceived Academic Control; but not with Academic Self-Esteem. Table 12 indicates that Formal Reasoning predicted success in all science courses. Perceived Academic Control, and Self-Concept predict success in CÉGEP biology courses, but not in physics, chemistry, and math.

Table 11. Correlation between Formal Reasoning (total scores) and motivational factors.

Motivational Factor	Pearson product correlation	Sample size
Self-concept	.146 *	505
Academic Self-esteem	.067	503
Perceived Academic Control	.297 *	508

Significant at p = .001

Table 12. Predictors of success in CÉGEP Biology, Chemistry, Math, and Physics (average of all grades in discipline).

	Biology	Chemistry	Math	Physics
Formal Reasoning	0.35*	0.10*	0.17*	0.23*
Self-Concept	0.42*	0.04	0.03	0.07
Academic Self-Esteem	0.04	0.03	0.04	0.03
Perceived Academic Control	0.29*	0.04	0.07	0.07

* Significant at p = .05

4.1.3. Summary and Discussion of Study 1

Our goal in Study 1 was to determine the formal reasoning skills of CÉGEP students taking a chemistry course (Chemistry NYA). As in previous studies (Torkia-Lagacé, 1981), we found that students in Technology Programs were less skilled than students in Pre-university Science Programs. While 76.8% of the Pre-university students had attained the formal reasoning level, only 48.5% of the Technology students had attained the formal reasoning level. Moreover, less than 5% of the Technology level had attained the high formal reasoning level compared to 28% of the Pre-university students. Since, formal reasoning skills are significantly correlated to high-school grades (especially science grades) this may reflect different selection criteria in the different programs.

Similarly, we also found that female students were less skilled at formal reasoning than male students, with only 64.5% attaining the level of formal reasoning compared to 73% of the male students. Female students were significantly less skilled than male students at proportional reasoning. However, when we looked only at the Pre-university science students, this difference in formal reasoning ability was only found in 17 year olds. That is, older female students "caught up" to male students. This confirms the findings of Eckstein and Shamesh (1992) that female students develop formal reasoning skills more slowly, **but** attain the same level.

Formal reasoning skills were correlated to self-concept and perceived academic control. They also were significant predictors of achievement in CÉGEP science and math courses (especially Physics and Biology).

4.2 Study 2

4.2.1. Question: *Does an intervention designed to improve students' formal reasoning and attributions enhance student achievement?*".

Table 13 shows the influence of the intervention on students' total scores and scores for reasoning about correlations, proportions, probability, and combinations as measured with the modified ATFR. Students in the experimental group significantly outperformed students in the control group ($F = 2.36$; $df = 4, 119$; $p < .05$) on Formal Reasoning. Subsequent univariate tests indicated that students in the experimental group outperformed students in the control group on reasoning about proportions and combinations, but not about probability and correlations.

Table 13. Influence of the Intervention on the Formal Reasoning of Students in the Experimental (N=67) and Control (N=57) Groups.

Treatment	Formal Reasoning							
	Correlations		Proportions		Probability		Combinations	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Experimental	3.19	1.16	3.04*	1.08	3.21	0.79	2.22*	1.04
Control	2.75	1.55	2.53	1.32	2.89	1.13	1.74	1.16

* indicates the experimental means are statistically higher than the control means ($\alpha = .01$)

** indicates the experimental mean is higher than the control mean ($\alpha = .002$)

Table 14 shows that there were **no** significant differences on Academic Self-Efficacy, Self-Control, or Perceived Academic Control ($F = 1.02$, $df = 3, 119$, $p = .387$) between students in the experimental and control groups.

Table 14. Influence of the Intervention on Academic Self-Efficacy, Self-Concept, and Perceived Academic Control for Students in the Experimental (N=67) and Control (N=57) Groups.

Treatment	Motivational Variables					
	Academic Self-Efficacy		Self-Concept		Control	
	Mean	SD	Mean	SD	Mean	SD
Experimental	9.4	2.0	10.6	1.9	10.0	2.4
Control	9.7	1.9	10.4	2.0	10.3	1.7

Table 15 shows the influence of the intervention on students' performance on a lab and a final question. Students in the experimental group significantly outperformed students in the control group ($F^3 = 17.44$, df = 2, 118, p = < .001). Subsequent univariate tests indicated that students in the experimental group outperformed students in the control group on the lab question but not on the evolution question.

Table 15. Influence of the Intervention on Performance on a Lab Test and on a Final Exam for Students in the Experimental (N=65) and Control (N=56) Groups.

Treatment	Achievement Tests			
	Lab Question		Evolution	
	Mean	SD	Mean	SD
Experimental	3.64	0.59	6.83	0.95
Control	3.09	0.40	6.71	1.05

The Multivariate Analysis of Variance test indicated that the intervention did not have a significant effect on students' Academic Self-Efficacy, Self-control, or Perceived Academic Control (F=1.02, df=3, 119, p=.387).

Finally, Table 16 shows the significant correlations between Formal Reasoning and student performance on the achievement measures. Figures 6a and 6b show the association between formal reasoning stage and performance on the evolution and lab questions, respectively.

[3] Using SPSS, Multivariate General Linear Model

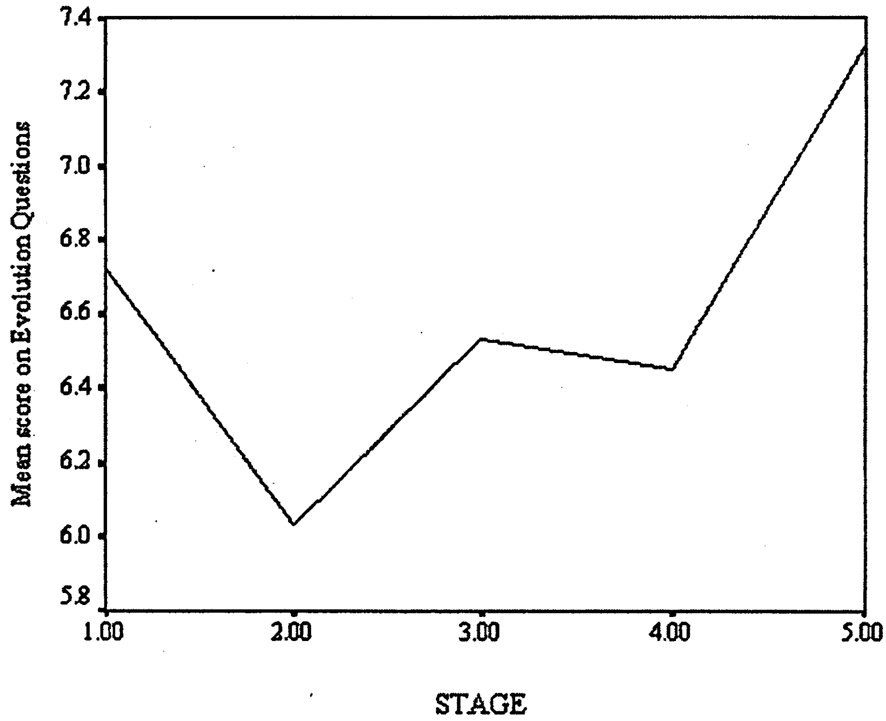
Table 16. Correlations between Formal Reasoning Measures and Achievement Measures for 124 students.

Formal Reasoning Measure	Correlation (r)	
	Lab Question	Evolution
Combinations	.63	.31
Correlations	.57	.20
Probability	.53	.28
Proportions	.61	.10
Total Score	.84	.31
Stage of Formal Reasoning	.80	.32

4.2.2. Summary and Discussion of Study 2

Our goal in study 2 was to determine whether an intervention which incorporated the explicit teaching of proportional reasoning and attributional retraining would enhance students' formal reasoning and academic achievement. The intervention increased students' skill at reasoning about proportions and combinations on the ATFR taken one week after the intervention. However, it did not influence students' self-concept, academic self-esteem, nor perceived academic control. Students told us that they did not relate to the students shown in the video and that they found the tape "boring". Furthermore, it is reasonable to expect that a longer (and more intense) intervention is needed to alter students' deep-seated feelings about themselves.

The intervention increased students' performance on the lab question (taken 6 weeks after the intervention) but not on the questions on evolution (taken 14 weeks after the intervention). The lab question was very similar to the intervention in that students were asked both times to calculate the real size of an object as seen under the microscope given information about the magnification and the field diameter at a second magnification. They thus had to take into consideration several variables and the relationship between the ratios of these variables. However, answering the question on evolution requires other formal reasoning skills (reasoning about forms of conservation beyond direct verification and the coordination of multiple frames of reference). Thus, it is not surprising that the intervention did not have an effect on students' achievement on the evolution questions.



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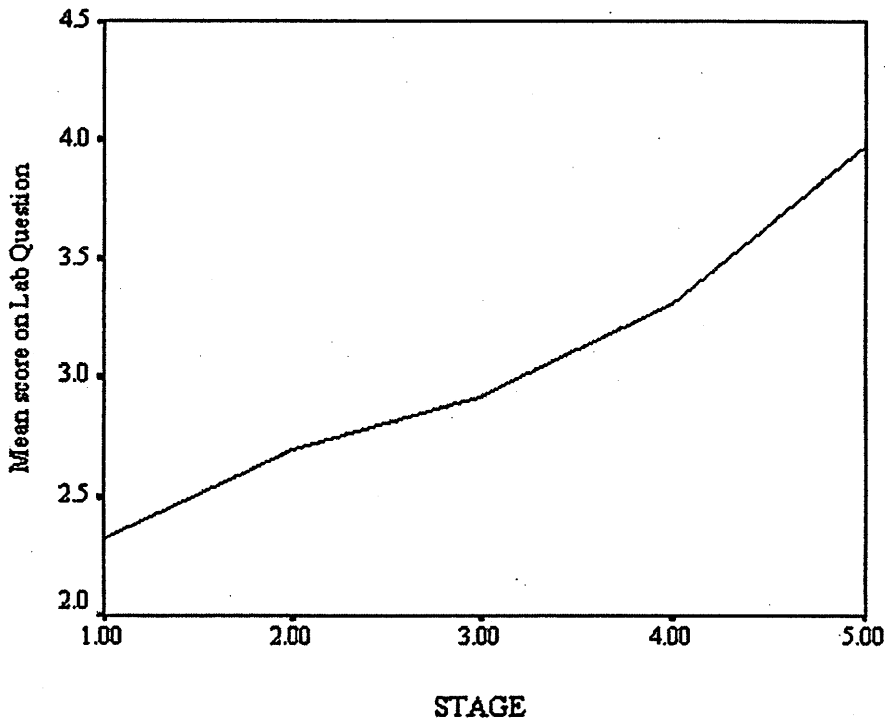


(b)

Figures 6a and 6b. Association between Formal Reasoning Stage (1 = Low Concrete, 2 = High Concrete, 3 = Transitional, 4 = Low Formal, and 5 = High Formal) and Performance on the Evolution (a) and Lab (b) questions, respectively.

4.3. Study 3

This study was quite different from the other two as the goal was to explore some of the techniques of assessing conceptual structures and to subsequently develop an efficient, reliable, and valid measure of students' conceptual structures. Therefore, it consisted of a cycle of activities in which the results of a first attempt were used to drive subsequent attempts. It also consisted of collecting both qualitative and quantitative data, and triangulating among the data collections. We subsequently used the data from this study to develop the method used in another study on students' mental models of evolution (d'Apollonia, Charles, and Boyd, 2004). We will therefore briefly describe what we learned from this study and subsequently show how it was applied to the second study.

4.3.1. Multiple Choice Tests

The students' scores on the three tests on the properties of water (Chemistry) and osmosis (Biology) are presented in Table 17. The correlation (Pearson's r) between the two tests was 0.43.

Table 17. Students' (N=31) Performance on Two Multiple-Choice Tests.

	Biology	Chemistry
Mean	57.7	65.2
Standard Deviation	17.8	17.5
25% Quartile	45.8	50
50% Quartile	58.4	70.8
75% Quartile	70.8	75.0

Figure 7 shows the distribution of grades on the two multiple choice test. It indicates that the scores for the biology test was normally distributed but not those on the chemistry test.

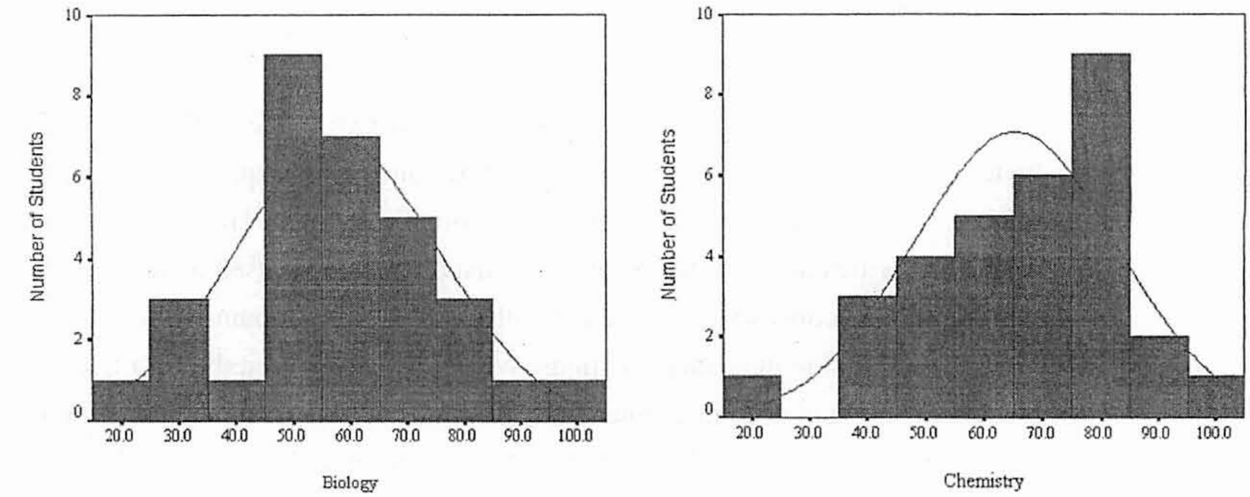


Figure 7. Distribution of grades on the Biology and chemistry tests.

Table 18. Degree of student understanding of concepts on chemistry of water and osmosis based on analysis of multiple-choice questions.

Test	Concept	Degree of Student Understanding (Percent of Students at level)		
		No understanding	Somewhat confused	Understood well
Water	Structure	15.6	28.1	56.3
	Composition	6.3	37.5	62.5
	Size	12.5	53.1	34.4
	Weight	34.4	18.8	46.9
Osmosis	Solutions	6.7	83.3	10.0
	Diffusion	46.7	30.0	23.3
	Osmosis	21.9	46.9	31.3

Most students understood the structure and composition of water; however, more students had difficulties understanding the size and weight of water molecules. This may be because these questions were unfamiliar. On the other hand, most students (in the order of 90%) had difficulties with questions about the nature of solutions. These results confirm anecdotal evidence from the biology teachers that many students have either not understood solutions in their chemistry courses or have not transferred their knowledge to biology. This lack of understanding leads to problems in understanding osmosis.

4.3.2. Essays

The quality of the essays was very poor, especially for the topics of osmosis. This may have been in part because the students were asked to write these short essays outside of class, and therefore did not take them seriously, or because of lack of knowledge (or forgetting) about the topic. Moreover, most students did not use many of the concepts they were asked to include. Thus, it is extremely difficult to decide whether students understood these concepts. The essays could be scored for accuracy and completeness, but this does not really tell us much about the conceptual structures for those students who did not write much. Tables 19, 20, and 21 show the two essays on osmosis and water written by three students: (Brian) who did well on both the multiple-choice tests and on the essays, (Claire) who was average on both, and (Paul) who did poorly on both.

As can be seen in the essays on osmosis, Brian appears to confuse the definitions of hypo-osmotic and hyper-osmotic as does Claire. Claire, in addition, appears to have misconceptions about the process of osmosis. Paul, on the other hand does not appear to know enough to write an essay that could be coded. This pattern was present for all the essays on Osmosis. Similarly, although all students knew the structure of water and polarity; they did not include many of the terms.

We computed the correlation coefficients between the scores on the multiple choice tests and the essays. Only the correlation between the essay on osmosis and the osmosis multiple-choice test was significant ($r = .86$). When we correlated the specific concepts in the essay with the scores for the misconceptions on the multiple choice tests, there were significant correlations on the Chemistry of Water essay for Structure, and on the Osmosis essay for Tonicity (.90) and the Process of Osmosis (.71). Thus, it does appear as if essays can be coded for students' conceptual structures; however there are problems with students writing skills that may lead to erroneous conclusions. Students often do not write about a specific topic and therefore their understanding of the topic remains "invisible". However, when they do write about specific concepts (e.g., structure of water or process of osmosis), their coded essay scores correlate to other measures of conceptual understanding.

Table 19. Brian's two essays on osmosis and water.

Osmosis is a special case of diffusion using water. Diffusion occurs when a concentration gradient exists, implying there exists a higher concentration of a particles in one solution than another. When a concentration gradient exists, the particles move from a high to low concentration, by passive transport meaning no external energy is required. When considering osmosis, a chemically pure solution of water will contain very little to no foreign particles. So, a solution with a higher concentration of particles will be hypo-osmotic to pure water. Given a semi-permeable membrane, water will pass through until the concentration is of both solutions will be equal. If the solution is hyper-osmotic, then there are fewer foreign particles in the solution. Iso-osmotic implies that both solutions have the same concentration. ***Water has a chemical structure of HYDROGEN-OXYGEN-HYDROGEN, so the oxygen is SP2 hybridized, giving bond angles of 120°. Since there are oxygen attached to hydrogen, Hydrogen bonding occurs which gives rise to very unique properties. Due to the molecular geometry of a water molecule, the molecule is polar. The hydrogen are partially positive while the oxygen is partially negative. A lone pair of electrons on the oxygen makes it an easy nucleophilic atom. Compared to the hydrogen, oxygen is a very big atom therefore the water molecule has a large molecular size, relative to the hydrogen counterpart. At room temperature, water is liquid. This is due to the h-bonding giving some unique properties, such as a very high boiling point, so water is able to stay liquid longer.***

Table 20. Claire's two essays on osmosis and water.

Osmosis is the passage of a solvent's particles through a cell's membrane. If the cell swells up, it is hypo-osmotic, which means that it absorbs the solvent. If it shrinks, it is hyper-osmotic, which means that it loses liquid. If nothing occurs then it is iso-osmotic. For the cell to be hypo-osmotic, the concentration of the solvent must be greater than that of the cell. If it is hyper-osmotic then the concentration inside the cell is greater than that o f the solvent. The diffusion of the solvent's particles is a form of passive transport, which means it requires energy. ***Water is a combination of two hydrogen and one oxygen atom. It can be found in the solid, liquid, or gaseous phase. Polar bonds are when a more negative molecule is attracted to a more positive molecule and they "stick" together. Covalent bonds are when two elements bond because of their valence electrons form an octet.***

Table 21. Paul's two essays on osmosis and water.

Osmosis is when a solvent in an area of high concentration diffuses down its concentration gradient towards an area of lower concentration by passive transport*, and therefore coded as missing*).* ***Water is composed of one oxygen atom which is connected to two hydrogen atoms by hydrogen bonding. Because of the strong hydrogen bonding, this relatively small molecule requires a lot of heat to make it go from liquid phase to gaseous phase.

4.3.3. Cognitive Maps

Students' similarity ratings were analyzed using MacKnot. All 31 students produced similarity ratings that produced interpretable cognitive maps. Figures 8 and 9 are the aggregated maps on osmosis and on the chemistry of water for all students, respectively.

When the similarity ratings are aggregated across all students, the map that is produced is more "interpretable" than many of the individual maps. This is in part because the common similarities are strengthened and idiosyncratic ones are diminished. For example, in the composite cognitive map on osmosis in Figure 8, diffusion is associated with concentration gradient and energy, osmosis is associated with water passive transport and membrane, solvent is associated with water. Similarly, in the composite cognitive map on chemistry in water in Figure 9, a negative charge is associated with electrons, the three phases are associated with water, etc.

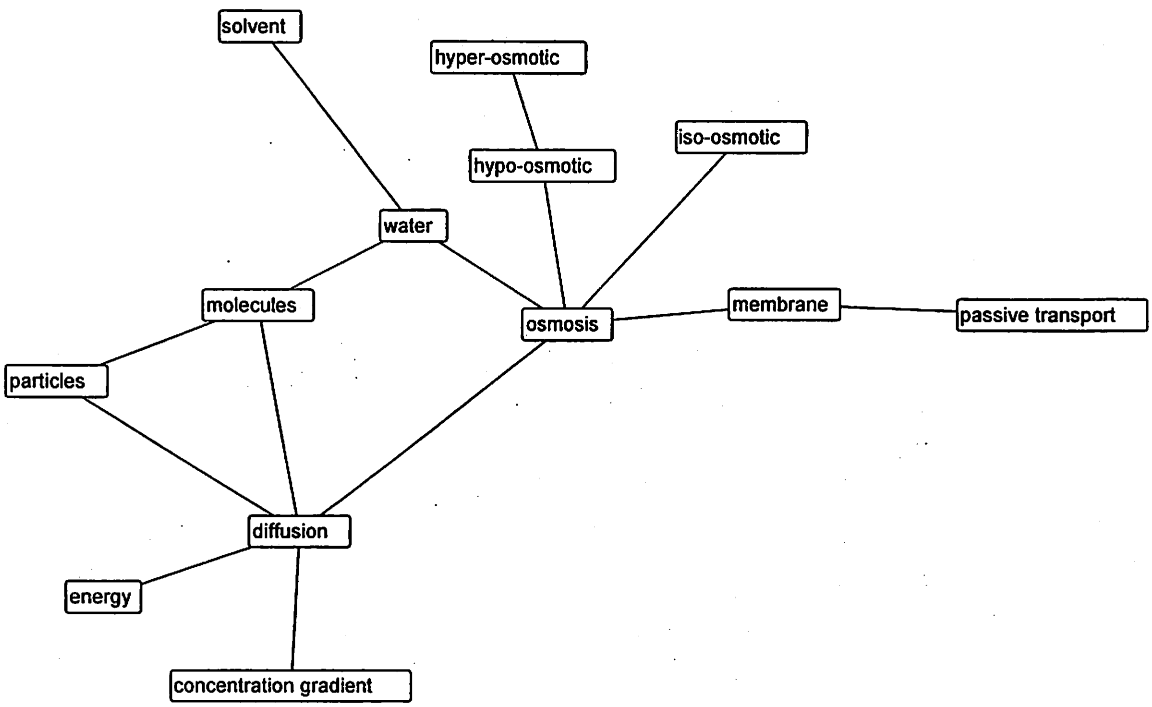


Figure 8. Composite cognitive map on the osmosis for 31 students.

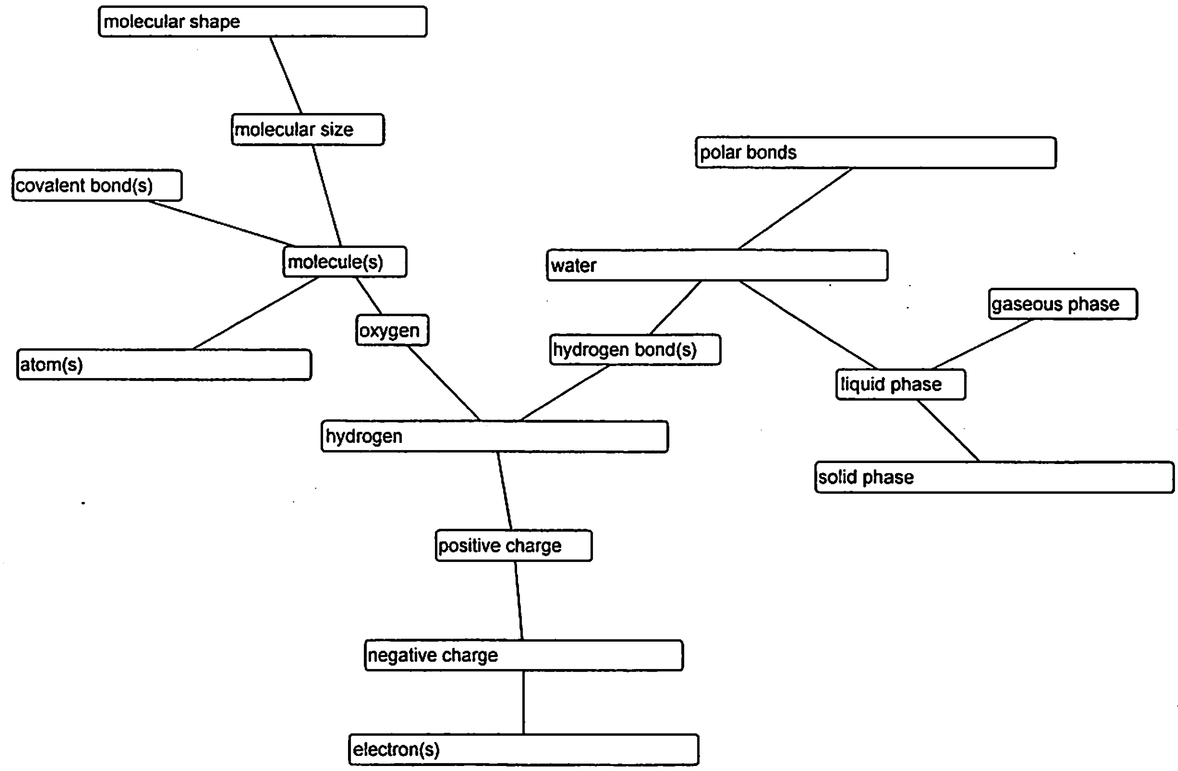


Figure 9. Composite cognitive map on the chemistry of water for 31 students.

Figures 10, 11, and 12 are the individual maps on osmosis and water for Brian, Claire, and Paul respectively. While the individual cognitive maps of the higher performing students (e.g., Brian) are relatively simple and interpretable, the cognitive maps of weaker students (e.g., Paul) are complicated (with all terms linked to other terms and many cross-connections). Thus, they are less interpretable. It appears as if weaker students have not differentiated the specific meaning among the terms. This is easily seen in Paul's cognitive map on osmosis.

The cognitive maps in this study were not correlated to the students' essays or performance on the multiple-choice tests since the cognitive maps indicate the presence of a concept and not whether the concept is understood. For example, we only chose the term passive-transport and did not include the term active transport. Therefore, we could not determine whether a student associated passive transport with diffusion and osmosis rather than with active transport. The terms were selected to indicate students' declarative knowledge of the topics, and not necessarily the underlying explanatory frameworks. Thus, we designed the follow-up study (d'Apollonia, Charles, & Boyd, 2004) described in Section

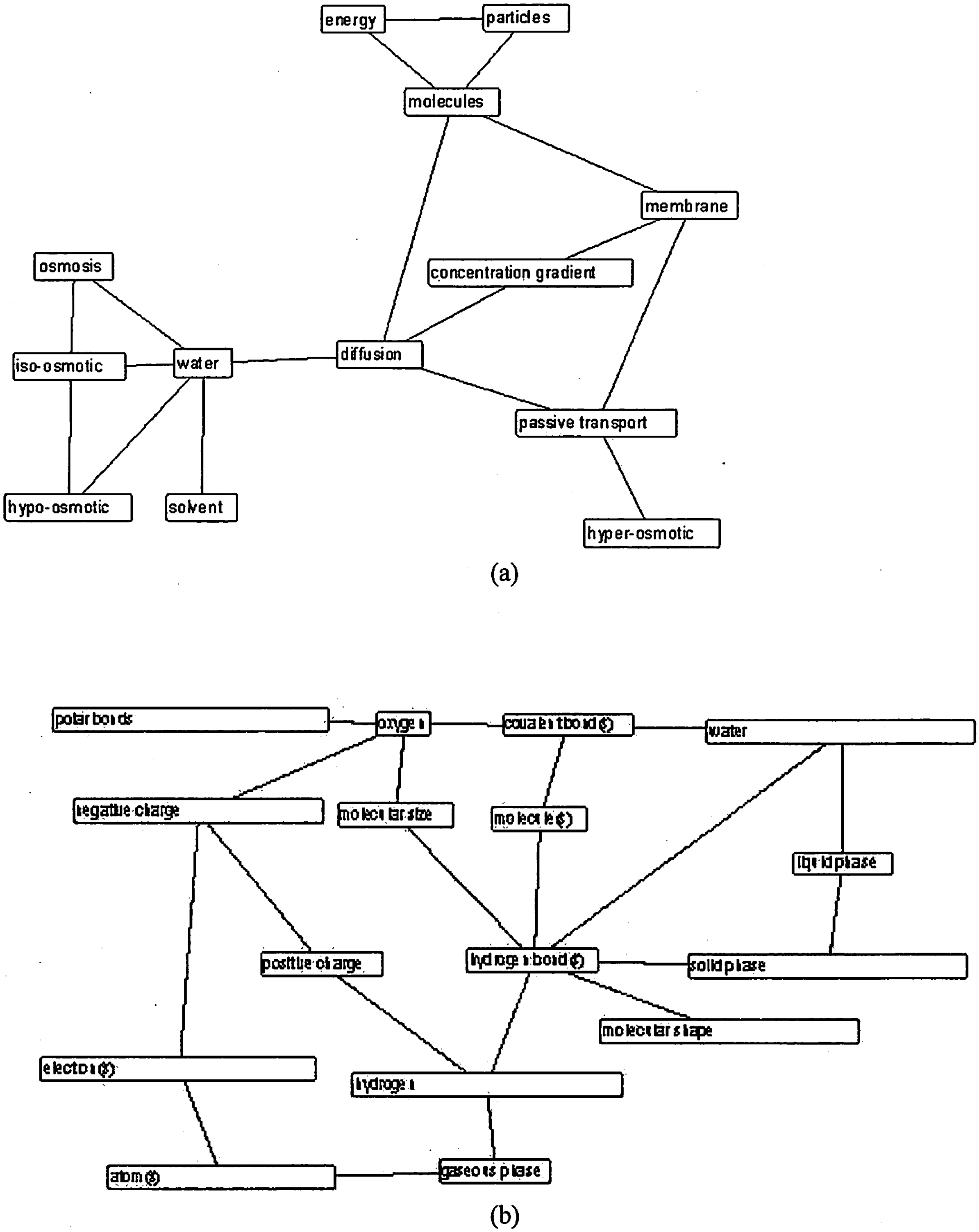
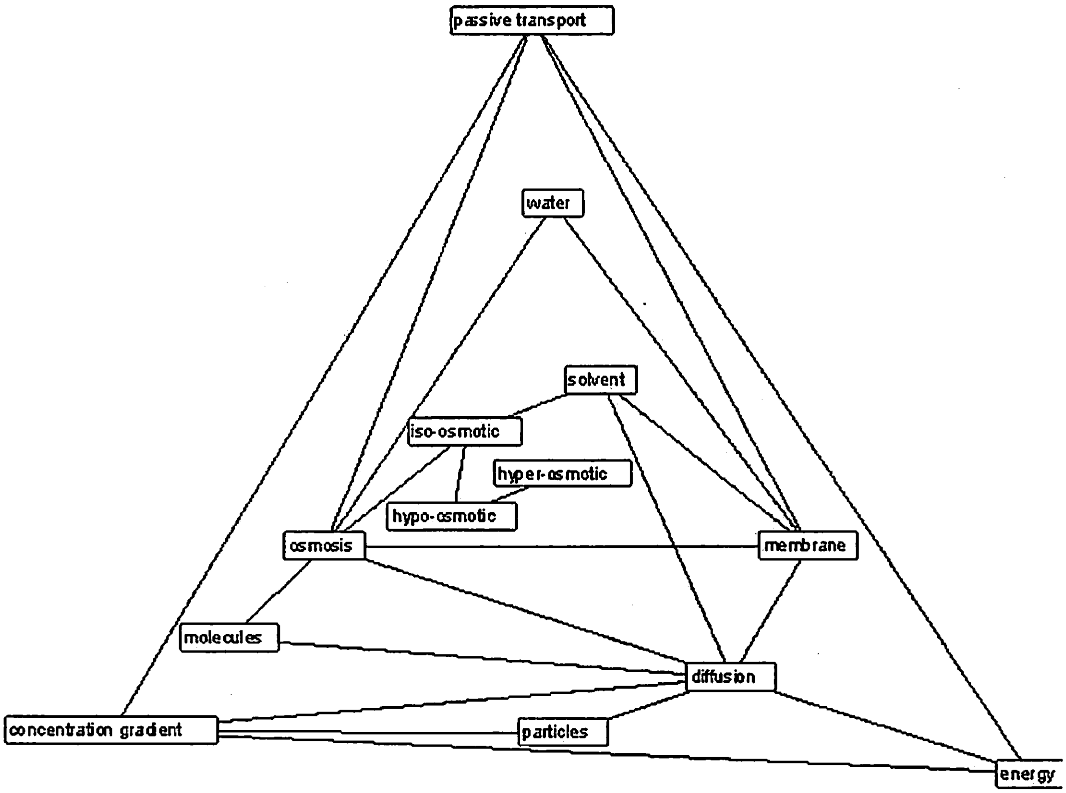


Figure 10. Brian's cognitive map produced from similarity ratings of osmosis (a) and chemistry of water (b) terms.



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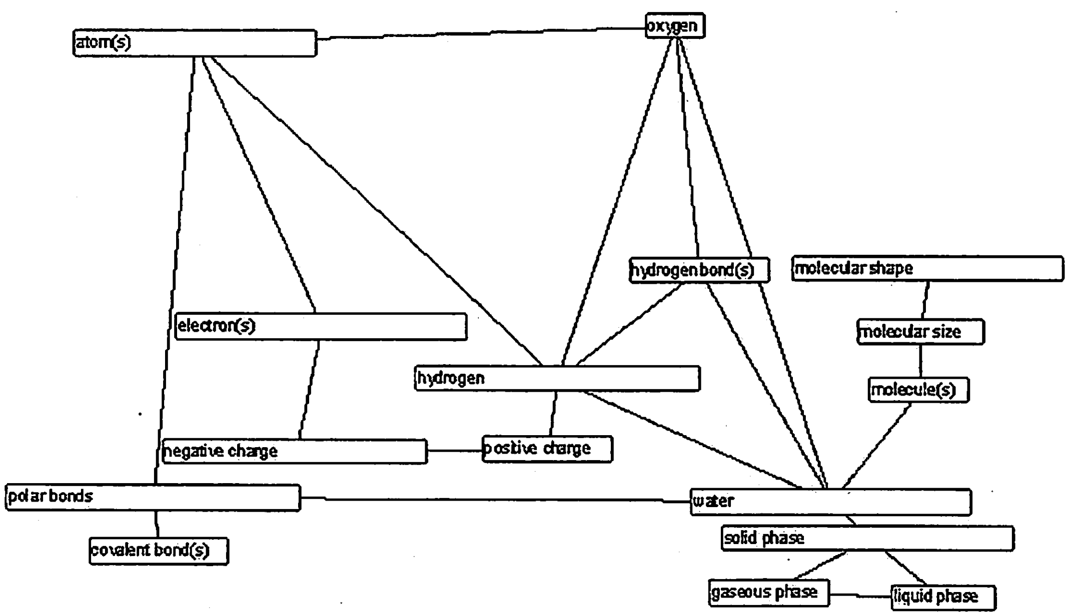

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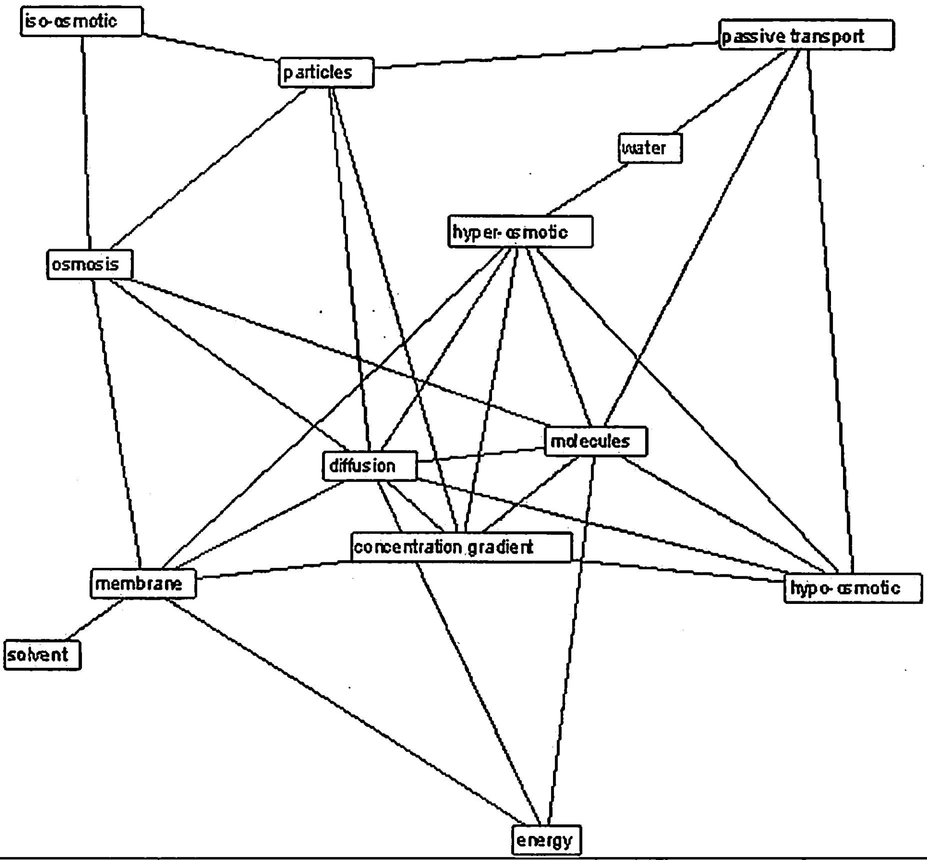
Figure 11. Claire's cognitive maps produced from similarity ratings of osmosis (a) and chemistry of water (b) terms



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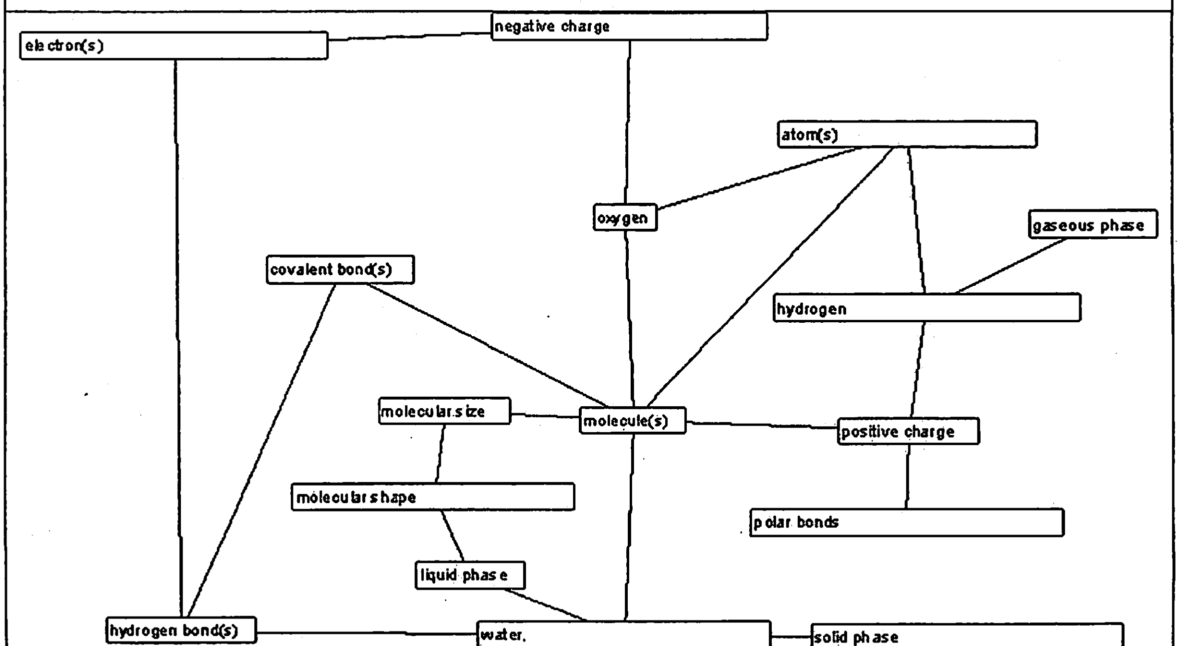


Figure 12. Paul's cognitive maps produced from similarity ratings of osmosis (a) and chemistry of water (b) terms

4.4 to explore the utility of using similarity ratings and scaling techniques to investigate changes in students' conceptual structures.

Similarity ratings and scaling techniques such as Pathfinder appear to give interpretable cognitive maps, especially if aggregated across a group. However, the choice of terms is a crucial decision and researchers may need to run several pilot tests to select the appropriate number and type of words. One technique that appears to be effective is to use the literature on misconceptions and contrast the conceptions of experts and naïve learners. Contrasting terms that capture the misconceptions of interest should then be included in the set of terms. We followed this procedure in the follow up-study on evolution, and found that the cognitive maps clearly portrayed the underlying explanatory frameworks of both teachers and their students. Thus, similarity ratings analyzed by MacKnot (or PCKnot) are an effective and valid method of capturing the conceptual structures of students. They are easy to administer and analyze, give readily interpretable representations (cognitive maps) of students' conceptual understanding, and as shown in the follow-up study on evolution

4.3.4. Summary and Discussion of Study 3.

Our goal in Study 3 was to explore various techniques of assessing students' conceptual structures. We investigated the utility of

- multiple-choice questionnaires in which the questions were selected (and subsequently coded) to measure specific misconceptions in two topics (the chemical nature of water and osmosis);
- essays on the same two topics coded to measure the same misconceptions; and
- cognitive maps produced from similarity ratings on two sets of terms on the two topics (chemistry of water and osmosis) analyzed using a scaling technique (Pathfinder analysis).

The students' overall scores on the multiple choice tests indicate that they appeared to understand the two topics. However, a better method of assessing their understanding is to code the questions and investigate students' performance on specific concepts. The multiple-choice tests were found to reliably measure four concepts in the Chemistry of Water topic (Structure, Composition, Size, and Weight) and three in the Osmosis topic (Solutions, Diffusion, and Osmosis). The students who volunteered for this study appeared to understand the Chemistry of Water topic but had difficulty with the Osmosis topic. This appeared to be in part because of difficulties in relating properties of solutions to the movement of solvent and solute particles during diffusion and osmosis. This technique appears to have promise; however, the specific wording of the questions needs to be investigated since students may have not done well on some concepts (Size and Weight) in part because of unfamiliarity with some of the questions and in part because they were not used to thinking about the size and weight of molecules..

Many students did not incorporate the requested words in essays. Thus, it is difficult to use their essays to assess their conceptual structures. In general, the students who were high-achievers wrote more than the low-achievers. This may reflect their general language and writing skills, rather than their understanding of the topics. Thus, one of the problems of using essays to assess students' conceptual structures is eliciting sufficient written work to subsequently code into types of misconceptions. We did find significant correlations between students' scores on the multiple-choice tests and essays for the total score on the Osmosis test, and for the Tonicity, Process of Osmosis, and Structure of Water sub-scores. Coding student essays is extremely time-consuming; however, if one is successful in eliciting the concepts they do provide clear evidence of students' misconceptions.

The students' similarity ratings produced readily interpretable cognitive maps for those students that performed well on the essays and multiple choice questions.. In those cases in which students wrote about the relationships between specific terms, the same relationships could be seen in their essays. When students left concepts out of their essays, the relationships between the same concepts were "messy" on their cognitive maps. When students' cognitive maps were averaged to produce the composite cognitive maps, the cognitive map became much more interpretable. This suggests that similarity ratings may provide easily collected evidence of what is happening during classroom instruction.

Thus, similarity ratings analyzed with MacKnot (or PCKnot) are an effective and valid method of capturing the conceptual structures of students. They are easy to administer and analyze, give readily interpretable representations (cognitive maps) of students' conceptual understanding, and as shown in the follow-up study on evolution are sensitive to instructional interventions.

4.4. Follow-up Study

We subsequently carried out a study (d'Apollonia, Charles, & Boyd, 2004) in which we investigated the impact of introducing college students to complex adaptive systems on their subsequent mental models of evolution compared to those of students taught in the same manner but with no reference to complex systems. We derived the mental models by analyzing similarity ratings (of 12 evolutionary terms) by the methods described in this report. The cognitive maps of four domain experts were coherent and consistent with theories of evolution. Multidimensional scaling revealed two underlying dimensions (role of chance and emergent levels). Thus, it appears that the cognitive maps captured both the declarative knowledge of evolution and the underlying explanatory framework.

The students' mental models were significantly similar to their teachers' mental models and were correlated to their performance on an essay on evolution. Furthermore, students' who had been introduced to complex systems had mental models significantly more similar to the teacher's mental model than did students not introduced to complex systems. The differences between the experts' composite cognitive map on evolution and that of students' is presented in Figure 13.

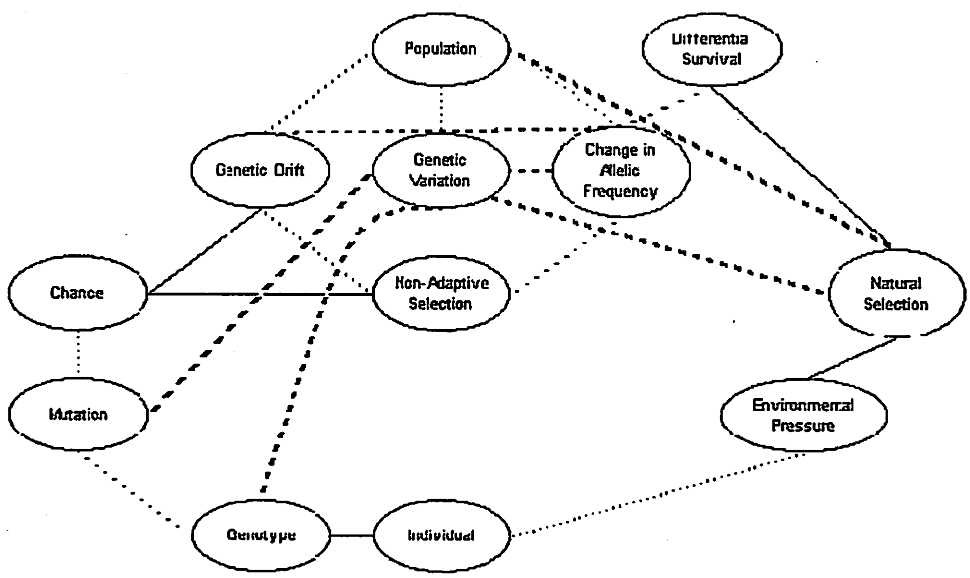


Figure 13. Students' composite cognitive map of evolution compared to that of experts'. The dotted lines are the links missing relative to the experts' maps. The bold dashed lines are the links added by the students.

GENERAL DISCUSSION AND CONCLUSIONS

Students in Technology Programs, especially female students, have low formal reasoning skills. More than 50% of them are either still functioning at the concrete level or are transitional. Thus, they are inconsistent at applying these reasoning skills across problem sets, especially in domains that they are learning for the first time. They are especially low at reasoning about proportions, a skill that is associated with success in learning science. However, it appears that with time female students (at least in the Science Programs), "catch-up" and attain the same formal reasoning level as their male counterparts. Another explanation for the "catch-up" could be that unsuccessful students drop out. Interventions that explicitly teach formal reasoning skills and include attributional training do enhance both formal reasoning skills and achievement. Thus, it would be relatively easy to incorporate formal reasoning exercises into courses taught to Science and Technology students in their first semester. This might enhance their achievement and motivation to continue in science.

It is relatively easy to assess students' conceptual structures by collecting similarity ratings and analyzing them with the Pathfinder algorithm. Cognitive maps are readily interpretable and are sensitive to instructional interventions. However, the cognitive maps appear to portray all possible associations that a specific student can make among concepts. When a student writes an essay, he or she makes a conscious choice of which concepts to highlight. Therefore, the two tasks are not really comparable. The cognitive maps portray the "reservoir" of concepts that a given student has available; while the essays demonstrate how a given student processes his or her domain knowledge to produce the essay.

Formal reasoning skills are necessary for the reorganization and restructuring of the conceptual network during both the knowledge acquisition phase and during the production of the essay. It would be interesting to carry out a longitudinal study in which one observed the changes in students' cognitive maps and correlated them with the students' formal reasoning skills. For example, low scores in proportional reasoning may make it more difficult for students to see that the new knowledge to be learned has the same relationship to some aspects of prior knowledge. They would then add on the new knowledge, rather than restructure their prior knowledge to include it.

REFERENCES

Adelson, B. (1981). "Problem solving and the development of abstract categories in programming languages." Memory and Cognition 9: 422-433.

Adey, P.S., Shayer, M., & Yates, C. (1989). Thinking science: Student and teachers' materials for the CASE intervention. London, Mccacmillan.

Adey, P.S. & Shayer, M. (1990). Accelerating the development of formal thinking of middle and high school pupils. *Journal of Research in Science Teaching*, 27, 267-285.

Alexander, P.A. & Kulikowich,J.M. (1992, April). *Learning from physics text.* Paper presented at the American Educational Research Association, San Francisco, CA.

Anderson, C. & Bishop, B. (1986). Evolution by natural selection: A teaching module. ERIC document, Research Series No. 165. ED269254.

Anderson, J. & Bower, G. (1973). Human Associative Memory. Washington, DC: Winston.

Anderson, J. R. (1983). A spreading activation theory of memory. Journal of Verbal Learning and Verbal Behavior, 22, 261-295 Arlin, P.K. (1982). A mutitrait-multimethod validity study of a test of formal reasoning. *Educational and Psychological Measurement*, 42, 1077-1088.

Arlin, P.K. (1984). *Arlin test of formal reasoning: Test manual*. East Auroa, NY: Slosson Educational.

Ausubel, D.P. (1963).*The psychology of meaningful verbal learning.*New York: Grune & Stratton, Inc.

Ausubel, D.P. (1968). *Educational Psychology: A cognitive view.* New York: Holt, Rinehart and Winston.

Berenson, S.B., Carter, G., & Norwood, K.(1992). The At-risk student in college developmental algebra. School Science & Mathematics, 92 (2), 55-58.

Bitner, B.L. (1991). Formal operational reasoning modes: Predictors of critical thinking abilities and grades assigned by teachers in science and mathematics for students in grades nine through twelve. *Journal of Research in Science Teaching*, 28,.

Bransford, J.D., Vye, N., Kinzer, C., & Risko, V. (1990). *Teaching thinking and content knowledge: toward an integrated approach.* In B.F. Jones & L. Idol (Eds.)., Dimensions of thinking and cognitive instruction (pp. 381-415). Hillsdale, NJ: Lawrence Erlbaum Associates.

Brooks, H. (1989). *Scientific literacy and the future labor force.* Unpublished manuscript, Harvard University, Cambridge, MA.

Caramazza, A., McCloskey, M, & Green, B. (1981). Naive beliefs in "sophisticated subjects: Misconceptions about trajectories of objects. *Cognition*, 9, 117-123.

Cavallo, A. (1991). *The relatonship between students' meaningful learning orientation and their mental models of meiosis and genetics.* Unpublished doctiral dissertation. Syracuse University.

Chase, W. G., & Simon, H. A. (1973). The mind's eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215-281). New York: Academic Press.

Charles, E. S.A. (2003). *An ontological approach to conceptual change: The role that complex systems thinking may play in providing the explanatory framework needed for studying contemporary sciences.* Unpublished doctoral dissertation, Concordia University, Montreal, Canada.

Chi, M.T.H. (2000). *Misunderstanding emergent processes as causal.* Paper presented at the Annual Conference of the American Educational Research Association, April 2000.

Chi, M.T.H. (2004). Common sense conception of emergence. *Journal of the Learning Sciences.* (in press)

Chi,M.T.H., Feltovitch, P.J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121-125.

Chi,M.T.H., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. SSternberg (Ed.). *Advances in the psychology of human intelligence.* (Vol. 1). Hillsdale, NJ: Lawrence Erlbaum Assoc.

Chi, M. T. H., Hutchinson, J. E., & Rosin, A. F. (1989). How inferences about novel domain-related concepts can be constrained by structured knowledge. Merrill-Palmer Quarterly, 35, 27-62.).

Chi, M.T.H. & Roscoe, R.D. (2002). The processes and challenges of conceptual change. In M. Limón & L. Mason (Eds.), *Reconsidering conceptual change. Issues in theory and practice* (pp. 3-27). Netherlands: Kluwer Academic Publishers.

Chi, M.T.H., Slotta, J. D., & deLeeuw, N. (1994). From things to processes: a theory of conceptual change for learning science concepts. *Learning and Instruction,* 4, 27-43.

Chi, M. T. H. (1993). Barriers to conceptual change in learning science concepts: A theoretical conjecture. In W. Kintsch (Ed.), Proceedings of the Fifteenth Annual Cognitive Science Society Conference (pp. 312-317). Hillsdale, NJ: Erlbaum.

Chinn, C. & Brewer, W. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of educational research*, 63(1), 1-49.

Chinn, C. & Brewer, W. (1998). An empirical test of a taxonomy of responses to anomalous data in science. *Journal of research in science teaching* , 35(6), 623-654.

Cho, H., Kahle, J.B., & Norland, F.H. (1985). An investigation of high school biology textbooks as sources of misconceptions and difficulties in genetics and some suggestions for teaching genetics. *Science Education*, 69, 707-719.

Conseil des Collèges, Gouvernement du Quebec.(1988). *La réussite, les échecs et les abandons au collégial*Churchland & Sejnowski, 1990)

Coll, R.K. & Treagust, D.F., (2002). Learners' use of analogy and alternative conceptions for chemical bonding: A cross-age study. *Australian science teachers' journal*, 48(1), p.24-32.

Culliton, B. J. (1989, February 3). The dismal state of scientific literacy. *Science,* p. 600.

Dansereau, D.F. (1988). Cooperative learning strategies. In C.E. Weinstein, E.T. Goetz, & P.A. Alexander (Eds.). *Learning and study strategies: Issues in assessment, instruction, and evaluation.* San Diego: Academic Press, Inc.

d'Apollonia, Charles, and Boyd (2004). Acquisition of Complex Systemic Thinking: Mental Models of Evolution. Educational Research and Evaluation (in press).

d'Apollonia, De Simone,C., Dedic, H., Rosenfield, S., & Glashan, A. (1993). *Cooperative Networking:A method of promoting understanding in the sciences.* Final Report submitted to Programme d'Aide à la rescherche sur l'enseignement et l'apprentissage (PAREA), Gouvernement du Quebec. ISBN 0-9696728-1-0

d'Apollonia, S., & Glashan, A. *(1992).Cooperative learning in a CEGEP science class.* Final Report submitted to Programme d'Aide à la rescherche sur l'enseignement et l'apprentissage, Gouvernement du Québec. ISBN 0-9696728-0-2

d'Apollonia, De Simone,C., Dedic, H., Rosenfield, S., & Glashan, A. (1993). *Cooperative Networking:A method of promoting understanding in the sciences.* Final Report submitted to Programme d'Aide à la rescherche sur l'enseignement et l'apprentissage (PAREA), Gouvernement du Quebec. ISBN 0-9696728-1-0

deKleer, J. & Brown, J.S, "Assumptions and Ambiguities in Mechanistic Mentat Models." in D. Genter & A.L. Stevens (Eds.) Menial Models. Hillsdale, NJ: Erlbaurn (1983): pp 155-190.

Demastes, S.S., Good, R.G., & Peebles, P. (1995). Students' conceptual ecologies and the process of conceptual change in evolution. *Science education*, 79(6), 637-666.

diSessa, A.A., Sherin, B., (1998).What changes in conceptual change? *International journal of science education*, 20 (10), 1155-1191.

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education*, 5, 61-84.

Dweck, C.S., & Leggett, E.L. (1988). A social-cognitive approach to motivation and personality. *Psychological Reviews*, 95, 256-273.

Eckstein, S.G. & Shemesh, M. (1992). The rate of acquisition of formal operational schemata in adolescence: A secondary analysis. *Journal of Research in Teaching Science*, 29, 441-451.

Eckstein, S.G. & Shemesh, M. (1993). Stage theory of the development of alternative conceptions. *Journal of Research in Science Teaching*, 30, 45-64.

Egan, D.E. & Schwartz, B.J. (1979). Chunking in recall of symbolic drawings. Memory and Cognition, 7, 149-158.

Epstein, H. T. (2001) An Outline of the Role of Brain in Human Cognitive Development. *Brain and Cognition*, 45, 44-51

Ericsson, K. A. & Simon, H. A. (1984). *Protocol analysis: Verbal reports as data.* Cambridge, MA: The MIT Press.

Eylon, B. S. & Linn, M. C., (1988). Learning and instruction: An examination of four research perspectives in science education. *Review of Educational Research,* 58, 251-301.

Ferrari & Chi, M.T.H. (1998). The nature of naïve explanations of natural selection. *International journal of science education*, 20(10), 1231-1256.

Flexer, B.K. & Roberge, J.J. (1983). A longitudinal investigation of field dependence-independence and the development of formal operational thought. *British Journal of Educational Psychology*, 53, 195-204.

Forsterling, F. (1985). Attributionaql retraining: A review. *Psychological Bulletin*, 98, 495-512.

Frederiksen, C.H. (1975). Representing logical and semantic structure of knowledge acquired from discourse. *Cognitive Psychology*, 7, 371-458,

Frederiksen, C.H. & Breuleux, A. (1990). Monitoring cognitive processing in semantically complex domains. In N.Frederiksen, R. Glaser, A. Lesgold, & M.G. Shafto (Eds.).*Diagnostic monitoring of skill and knowledge acquisition.* Hillsdale, NJ: Lawrence Erlbaum Assoc.

Garner, R. (1990). When children and adults do not use learning strategies: Toward a theory of settings. *Review of Educational Research*, 60, 517-529.

Gentner, D., & Stevens A.L. (1983). *Mental models.* Hillsdale, NJ: Erlbaum Press.

Glaser, R., Lesgold, A., and Lajoie, S. (1987). Toward a cognitive theory for the measurement of achievement. In R. R. Ronning, J. Glover, J. C. Conoley, and J. C. Witt (Eds.), *The influence of cognitive psychology on testing and measurement* (pp. 41-85). Hillsdale, NJ: Erlbaum;

Grant, D. (1990). Putting life into science teaching. The Globe and Mail. Saturday September 8.

Griffith, A.K., & Preston, K.R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching*, 29, 611-628.

Hauslein, Good & Cummings, (1992). Biology Content Cognitive Structure: From Science Student to Science Teacher.Journal of Research in Science Teaching. 29, 939-964.

Hautamaki, J. (1984). *The measurement and distribution of Piagetian stages of thinking in Finnish comprehensive schools.* Publications in Social Sciences, University of Joensuu, Finland.

Inhelder, B. & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. New York: Basic Books.

Jacobson, M. J., & Archodidou, A. (2000). The design of hypermedia tools for learning: Fostering conceptual change and transfer of complex scientific knowledge. *Journal of the learning sciences*, 9(2), 149-199.

Johnson-Laird, P.N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness*. Cambridge, MA: Harvard University Press.

Klausmeier, H.J. (1990). Conceptualization. In B.F. Jones & L. Idol (Eds). *Dimensions of thinking and cognitive instruction.* Hillsdale, NJ: Lawrence Erlbaum Assoc.

Koubek, R.J, & Mountjoy, D. N. (1991).Toward a Model of Knowledge Structure and a Comparative Analysis of Knowledge Structure Measurement Techniques. ERIC_NO: ED339719

Kurfiss, J.(1983). *Intellectual, psychological, and moral development in college: Four major theories*. in Manual for Project QUE (Quality Undergraduate Education), Council for Independent Colleges, Washington, DC.

Lawson, A.E. (1978). The development and validation of a classroom test of formal reasoning. *Journal of Research in Science Teaching*, 15, 11-24.

Lawson, A.E. (1985). A review of research in formal reasoning and science teaching. *Journal of Research in Science Teaching*, 22, 569-617.

Lawson, A.E. & Bealer, J.M. (1984). Cultural diversity and differences in formal reasoning ability. *Journal of Research in Science Teaching*, 21, 735-743.

LESTER (2004). Learning Science and Technology Repository. http://lester.rice.edu/DesktopDefault.aspx

Lewin, K. (1989). Planning for scientific and technological development. In T. Huse'n & T. N. Postlethwaite (Eds.), *International encyclopedia of education: Research and Studies, (Supplementary Vol. 1*). Oxford, England: Pergamon Press.

Lim, T-K. (1993, April). Gender-related differences in intelligence: Application of confirmatory factor analysis. Paper presented at the annual meeting of the American Educational Research association. Atlanta, GA.

Logan, R.D. & O'Hearn, G.T. (1982). Thought-style and life-style: Some hypothetical relationships. *Science Education*, 66, 515-530.

Logsdon, D.,& Shore, B. (1982). Student needs and services: Undergraduate and mature student perceptions. Montreal,QC: Centre for Teaching and Learning Services, McGill University.

Lunzer, E. (1986. Cognitive development: Learning and the mechanisms for change. in G.D. Phye and T. Andre (eds.). Cognitive classroom learning: Understanding, thinking, and problem solving. San Diege, CA: Academic Press, Inc.

McKeachie, W.J., Pintrich, P.R., Lin, Y-G., Smith, D.A.F., & Sharma, R. (1990). *Teaching and Learning in the college classroom.* Technical Report No. 90-B-003.1. The University of Michigan, Ann Arbor, MI.

McKinnon, J. W. & Renner, J.W. (1971). Are colleges concerned with intellectual development? *American Journal of Physics, 39*, 1047.;

McNamara, T.P., Miller, D.L.,& Bransford, J.D. (1991). Mental models and reading comprehension. In R. Barr, M. Kamil, P. Mosenthal, & P.D. Pearson (Eds.). Handbook of Reading Research (Vol. 2). White Plains, N.Y: Longman.

Meece, J. L., Blumenfeld, P. C., & Hoyle, R. H. (1988). Students' goal orientation and cognitive engagement in classroom activities. *Journal of Educational Psychology, 80,* 514-523.

Menec, V. M.& Perry, R. P.(1995). Disciplinary Differences in Students' Perceptions of Success: Modifying Misperceptions with Attributional Retraining. *New Directions for Teaching and Learning.* 64, 105-12.

MEQ, 1993. Indicateurs sur la situation de l'enseignement primaire et secondaire, Quebec.

MEQ, 2003. Reaffirming the Mission of Our Schools. A new direction for success. *Report of the Task Force on Curriculum Reform* from http://www.meq.gouv.qc.ca/reforme/curricu/anglais/school.htm

Mosenthal, P.B. & Kirsch, I.S. (1992). Learning from exposition: Understanding knowledge acquisition from a knowledge model perspective. *Journal of Reading*, 35, 356:370.

Murphy, G.L., & Wright, J.C.(1984). Changes in conceptual structure with expertise: Differences between real-world experts and novices. Journal of Experimental Psychology: Learning, Memory, and Cognition, 10, 144-155.

Naveh-Benjamin, M., McKeachie, W.J., Lin, Y-G., & Tucker, D.G. (1986). Inferring students' cognitive structures and their development using the "ordered tree technique. *Journal of Educational Psychology*, 79, 130-140.

Nersessian, N. J. (1989). Conceptual change in science and in science education. *Synthese,*, 80, 163-183

Novak, J.D. & Musonada, D., (1991). A twelve-year longitudinal study of science concept learning. *American Educational Research Journal*, 28, 117-153.

Novak, J.D., & Gowin, D.B. (1984). *Learning how to learn.* New York, NY: Cambridge University Press.

Novak, J.D.(1988). Learning science and the science of learning. *Studies in Science Edu*cation, 15, 77-101.

Odom, A.L. & Barrow, L.H. 1995. Development and application of a two-tier diagnostic test measuring college biology students' understanding of diffusion and osmosis after a course of instruction. *Journal of Research in Science Teaching*, 32, 45-61.

Olson, J.R. & Biolsi, K.J. (1991). Technique for representing expert knowledge. In K.A. Ericsson & J. Smith (Eds.). *Toward a general theory of expertise* (pp240-285). Cambridge:Cambridge University Press.

Olson, J. & Reuter, H. (1987). Extracting expertise from experts: Methods for knowledge acquisition. Expert Systems, 4, 152- 168.

Perry, R. (1998) Personsl communications.

Perry, R. P., Hall, N. C., & Ruthig, J. C. (2004). Perceived (academic) control and scholastic attainment in higher education. In J. Smart (Ed.), Higher education: Handbook of theory and research. New York: Kluwer Academic/Plenum Publishers. (in press).

Pfundt, H., & Duit, R. (1994). *Bibliography. Students' alternative frameworks and science education.* (4th ed.) Kiel, Germany: IPN.

Pfundt, H. & Duit, R. (2003) *Bibliography: Pupils' alternative frameworks and science education.* Available online from http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html, accessed 21/05/03

Piaget, J. 1954. *The construction of reality in the child.* New York: Basic Books.

Piaget, J. (1972). Intellectual evolution from adolescence to adulthood. *Human Development*, 5, 1-12.

Perry, R, P. & Penner, K.S. (1990). Enhancing Academic Achievement in College Students through Attributional Retraining and Instruction. *Journal of Educational Psychology*, **82,** 262-71.

Pintrich, P.R., Brown, D.R., & Weinstein, C.E. (eds.). (1994). *Student motivation, cognition, and learning.* Hilldale, NJ: Lawrence Erlbaun, Assoc. Publishers.

Pintrich, P.R.,Marx,R.W.,& Boyle,R.A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom conceptual factors in the process of conceptual change. *Review of Educational Research,* 63, 167-199.

Posner, G., Strike, K., Hewson, P., & Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66(2), 211-227.

Ram, A., Nersessian N.J., Keil F.C. (1997) Conceptual change, Journal of the Learning Sciences, 6(1),1-2

Reyes, D. J., & Capsel, W. (1986). Piagetian cognitive development in some high-risk university freshmen. Equity and Excellence, 22, 86-89.

Roger, E. M. (1983). *Diffusion of innovations*(3rd ed.). New York: Free Press/Macmillan

Roth, K.J. (1990). *Developing meaningful conceptual understanding in science.* In Beau Fly Jones and Lorna Idol (Eds.). *Dimensions of thinking and cognitive instruction.*Hillsdale, NJ: Lawrence Erlbaum Assoc.

Royer, J.M., Cisero, C.A., & Carlo, M.S. (1993). Techniques and procedures for assessing cognitive skills. Review of Educational Research, 63, 201- 243.

Ruiz-Primo, M. A. & Shavelson, R. J. (1996). Problems and issues in the use of concept maps in science assessment. Journal of Research in Science Teaching, 33(6), 569-600.

Rumelhart, D.E. (1980). Schemata: the building blocks of cognition. In R.J. Spiro, B.C. Bruce, & W.F. Brewer (Eds.). Theoretical issues in reading comprehension. Hillsdale, N.J: Erlbaum

Rumelhart, D.E. & Norman, D.A. (1981). Accretion, tuning, and restructuring: Three modes of learning . In J.W. Cotton & Klatzky (Eds.).*Semantic factors in cognition.* Hillsdale, NJ: Lawrence Erlbaum Assoc.

Sanger, M. J., Brecheisen, D.M., & Hynek, B.M. (2001). Can computer animations affect college biology students' conceptions about diffusion and osmosis? *American Biology Teacher*, 63 (2), p.104-09.

Schaneveldt, R.W. (1990). Pathfinder Associative Networks: Studies in Knowledge Organization. Ablex Publishing Company

Schau, C., & Mattern, N. (1997). Use of map techniques in teaching applied statistics courses. The American Statistician, 51(2), 171-175

Shavelson, R. J., Ruiz-Primo, M. A., & Wiley, E. (2004). Windows into the Mind. *International Journal of Higher Education,* in press

Shayer, M. & Adey, P. (1993). Accelerating the development of formal thinking in middle and high school students IV: Three years after a two-year intervention. *Journal of Research in Science Teaching*, 30, 351-366.

Shayer, M. & Adey, P. (1992). Accelerating the development of formal thinking in middle and high school students III: Testing the permanancy of effects. *Journal of Research in Science Teaching*, 29, 1101-1115.

Shayer, M. & Wylam, H. (1978). The distribution of Piagetian stages of thinking in British middle and secondary school children. II: 14-16 year olds and sex differentials. *British Journal of Educational Psychology,* 48, 62-70.

Slotta, J.D. & Chi, M.T.H. (1999). *Overcoming robust misconceptions through ontological training*. Paper presented at the Annual Conference of the American Educational Research Association, Montreal, QC.

Strike, K. A. & Posner, G. J. (1985). Conceptual change view of learning and understanding. In L. West & A. L. Pines (Eds.), *Cognitive structures and conceptual change* (pp.211-231). Orlando, FL: Academic Press, Inc

Strike, K. A. & Posner, G. J. (1992). A revisionist theory of conceptual change. In R.Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive science, and educational theory and practice* (pp.147-176). Albany, NY: Sunny Press.

Struthers, C. W., & Perry, R. P. (1996). Attributional style, attributional retraining, and inoculation against motivational deficits. *Social Psychology of Education, 2,* 171-187.

Suits, J. P., (2000). *Conceptual change and chemistry achievement: A two-dimensional model*. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.

Tobias, S. (1985). Test anxiety: Interference, defensive skills, and cognitive capacity. Educational Psychologist, 20, 135-142.

Tobias, S. (1990). *They're not dumb, they're different: Stalking the second tier. An occasional paper on neglected problems in science education.* Tucson, AR: Research Corporation.

Tobin, K.G. & Carpie, W. (1981). The development and validation of a pencil and paper test of logical thinking. *Educational and Psychological Measurement*, 41, 413-424.

Torkia-Lagacé, M. (1981). *La pensée formelle chez les étudiants de collège 1: objectif ou réalité?*. Rapport final d'une recherche . CEGEP de Limilou

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. Learning and Instruction, 4, 45-69.

Vosniadou, S. & Brewer, W.F. (1994). Mental models of the day/night cycle. *Cognitive Science*, 18(1), 123-183.

Vosniadou, S. & Ioannides, C. (1998). From conceptual development to science education: A psychological point of view. *International Journal of Science Education*, 20(10), 1213-1230.

Walberg, H.J. (1991). Improving School Science in Advanced and Developing. Countries, *Review of Educational Research,* 61, No.1, 25-69.

Weiner, B. (1985). *An attributional theory of motivation and emotion.* New York: Springer-Verlag.

Weinstein, C.E., Zimmerman, S.A., & Palmer, (1988). *Assessing learning strategiesThe design and development of the LASSI.* In C.E. Weinstein, E.T. Goetz, & P.A. Alexander (Eds.). *Learning and study strategies: Issues in assessment, instruction, and evaluation.* San Diego: Academic Press Inc.

Wiley, E.W. (1998). *Indirect and Direct Assessment of Structural Knowledge in Statistics.* Stanford, CA: Stanford University School of Education

Wilson, J.M. (1994). Network representations of knowledge about clinical equilibrium: Variations with achievement. *Journal of Research in Science Teaching,* 31, 1133-1142.

Wilson, J.M. (1998)Differences in knowledge networks about acids and bases of year-12, undergraduate, and postgraduate chemistry students. Research in Science Education, 28, 429-446.

APENDIX 1

STUDENT BACKGROUND CHARACTERISTICS
AND
ARLIN TEST OF FORMAL REASONING

Please **do not mark** the questionnaire booklet. Answer each question directly on the **answer sheet.**

Please work as quickly and as accurately as you can. You will have forty-five minutes to complete the two questionnaires. If you finish before time is called, you may go back and check your answers. If you do not finish in forty-five minutes. and you do not have another class, you may take additional time to finish.

You are to indicate the best answer in each case by making a heavy black mark in the proper place on the answer sheet. Be sure that you mark your answer in the space whose number corresponds to the question you are answering. If you are not sure of the best answer to an item, make the best guess that you can. If you wish to change an answer you may do so, but be sure to erase the mark completely.

Please do not talk or share your answers with other students. Furthermore, your responses will be treated confidentially. Your teachers and your classmates will not be shown your individual responses.

THANK YOU FOR TAKING THE TIME TO COMPLETE THIS TEST

CONTINUED SUCCESS IN YOUR STUDIES.

Before we begin. make sure that you have filled in your **student number**, **group**, and **name** on the answer sheet. Please use a lead pencil and <u>not</u> a pen.

DIRECTIONS: You will find below a series of statements that are more or less true (or more or less false) descriptions of you. Please use the following four-point response scale to indicate how true (or false) each item is as a description of you.

Response Scale:

a. false
b. more false than true
c. more true than false
d. true

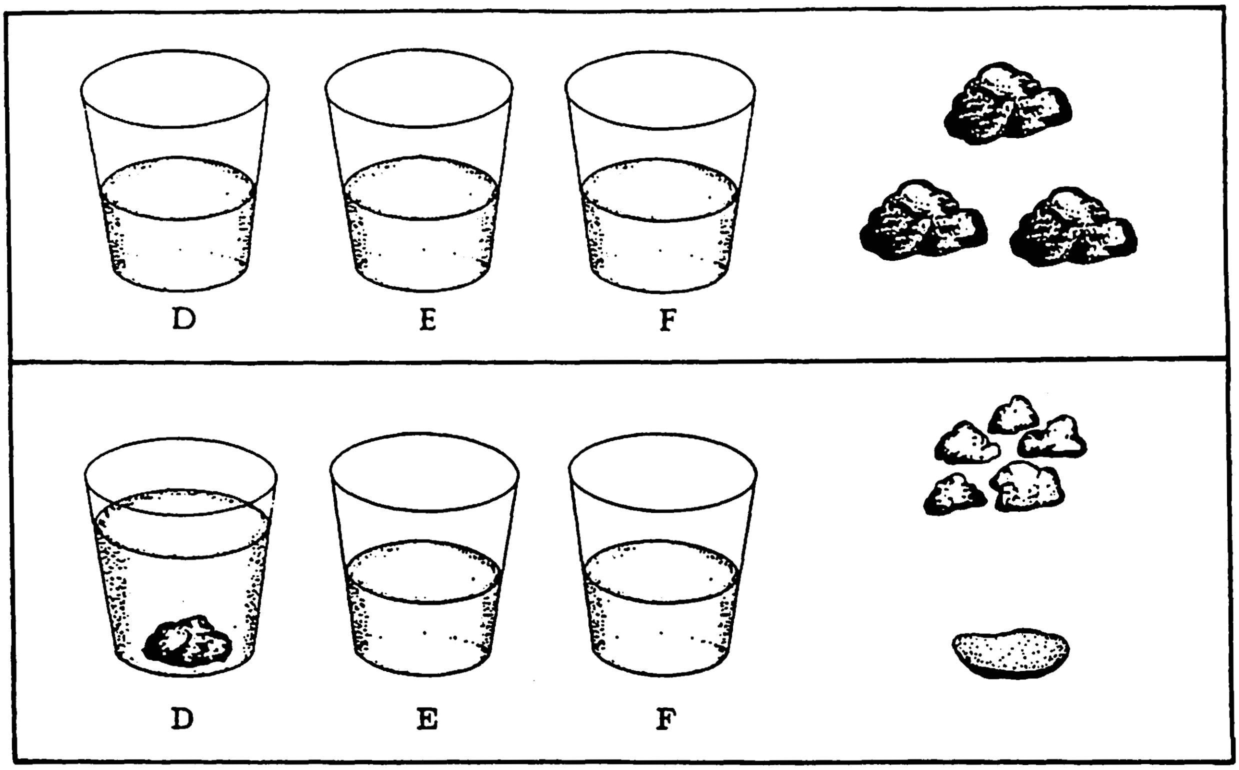
1. I feel that, as a student, I'm a person of worth, at least equal to other students.
2. I feel that, as a student, I have a number of good qualities.
3. All in all, I'm inclined to feel that I am a failure academically.
4. I am able to do things as well as most of my classmates.
5. I feel that, as a student, I do not have much to be proud of.
6. I take a positive attitude to myself as a student.
7. On the whole, I am satisfied with myself as a student.
8. I have a great deal of control over my academic performance.
9. There is little I can do about my academic performance.
10. I see myself as largely responsible for my academic performance in college.
11. My grades are basically determined by things beyond my control and there is little I can do to change that.
12. I expect to do extremely well in my CEGEP science courses.

13. What is your gender?
    a. female
    b. male

14. What is your age in years?
    a. less than 17 years.
    b. 17
    c. 18
    d. 19
    e. 20 and above

15. How much time do you intend to spend on science assignments and review per week?
    a. less than 5 hours
    b. between 5 and 8 hours
    c. between 8 and 11 hours
    d. between 11 and 14 hours
    e. more than 14 hours.

Please go on to the next section....



Three cups, (Cup D, Cup E, and Cup F) are partially filled with water. Beside the three cups are three balls of clay. These three balls are exactly the same size as each other. The first ball is placed in Cup D as shown. The water level in Cup D rises. Before placing the second ball into Cup E, it is flattened into a pancake shape as shown. The third ball of clay is broken into five pieces as shown and then placed into Cup F.

16 What do you think will happen to the water level in Cup E when this pancake shaped piece of clay is placed into it?

A. The water level will rise up higher than the level in cup D.
B. The water level will rise to half the level of cup D.
C. The water level will go up to the same height as that in cup D.
D. The water level will rise to one-fifth the height of that in cup D.

17 What is the reason for your answer to the question just above?

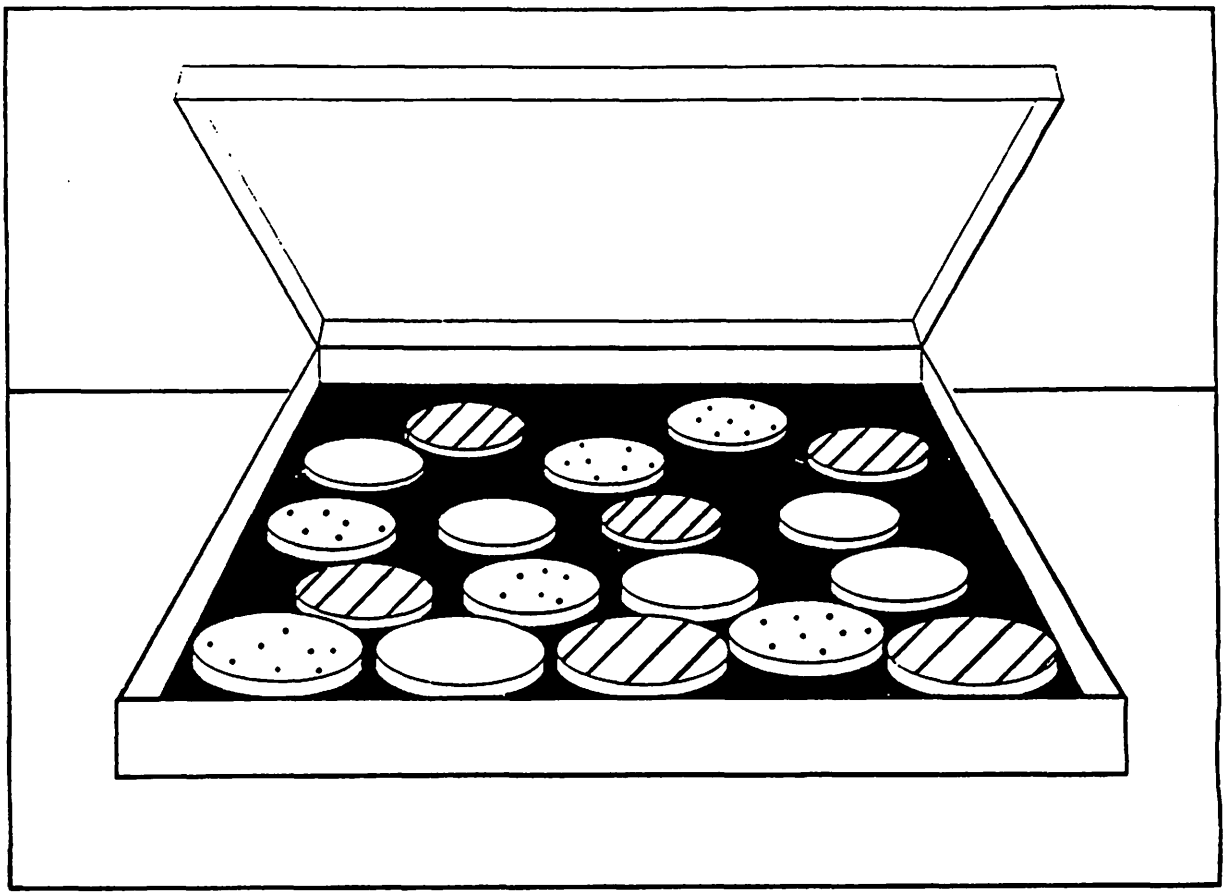
A. The pancake shape takes up more space.
B. The balls were the same size at the start.
C. The pancake shape is flat and therefore it takes up less space.
D. The ball and pancake weigh the same.

18 What do you think will happen to the water level in Cup F when the five small balls of clay are placed in it?

A. The water level will go up to the same height as that in Cup D.
B. The water level will NOT rise up as high as that in Cup D.
C. The water level will rise up higher than the level in Cup D.
D. The water level will rise one-fifth the height as that in Cup D.

19 What is the reason for your answer to the question just above?

A. The five balls of clay take up more space.
B. The balls were the same size before the one ball was broken into pieces.
C. The five small balls take up less room.
D. The five small balls weigh the same as the one large ball.



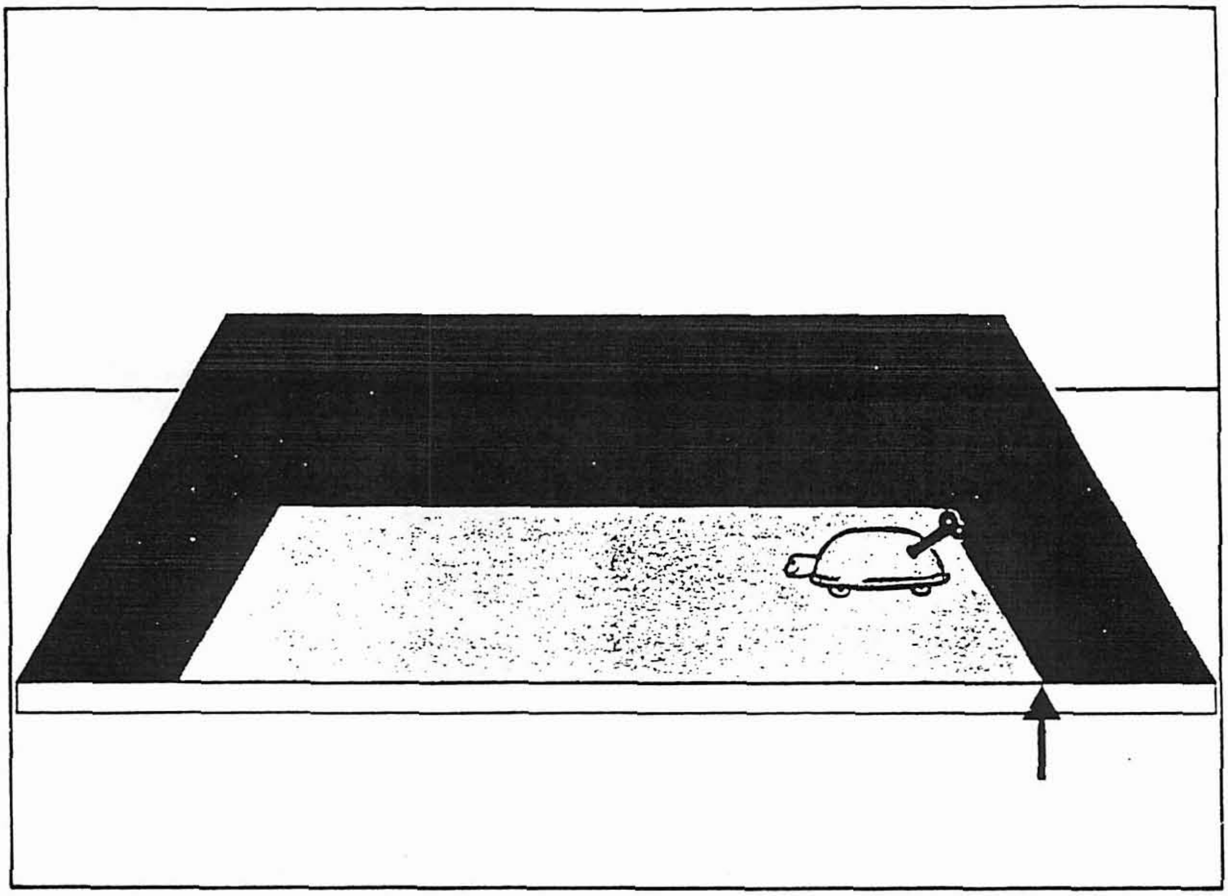
In a new game of chance, six plain tokens, six striped tokens and six dotted tokens are placed in a box as pictured above. The box is held above your head so that you cannot see the tokens. You are asked to draw one token out of the box.

20 What do you think your chances are of drawing a striped token on your very first draw?

A. One chance out-of-two.
B. One chance out-of-eighteen.
C. One chance out-of-twelve.
D. One chance out-of-three.

21 Why did you choose your answer for the question just above?

A. My chances are the same as those for flipping a coin and getting heads.
B. My chances are based on the fact that the number of striped tokens has to be compared to the total number of tokens.
C. My chances are good to draw it in the first two or three draws because I am lucky.
D. My chances are based on the fact that there are twelve tokens that are not striped and I need to eliminate these first.



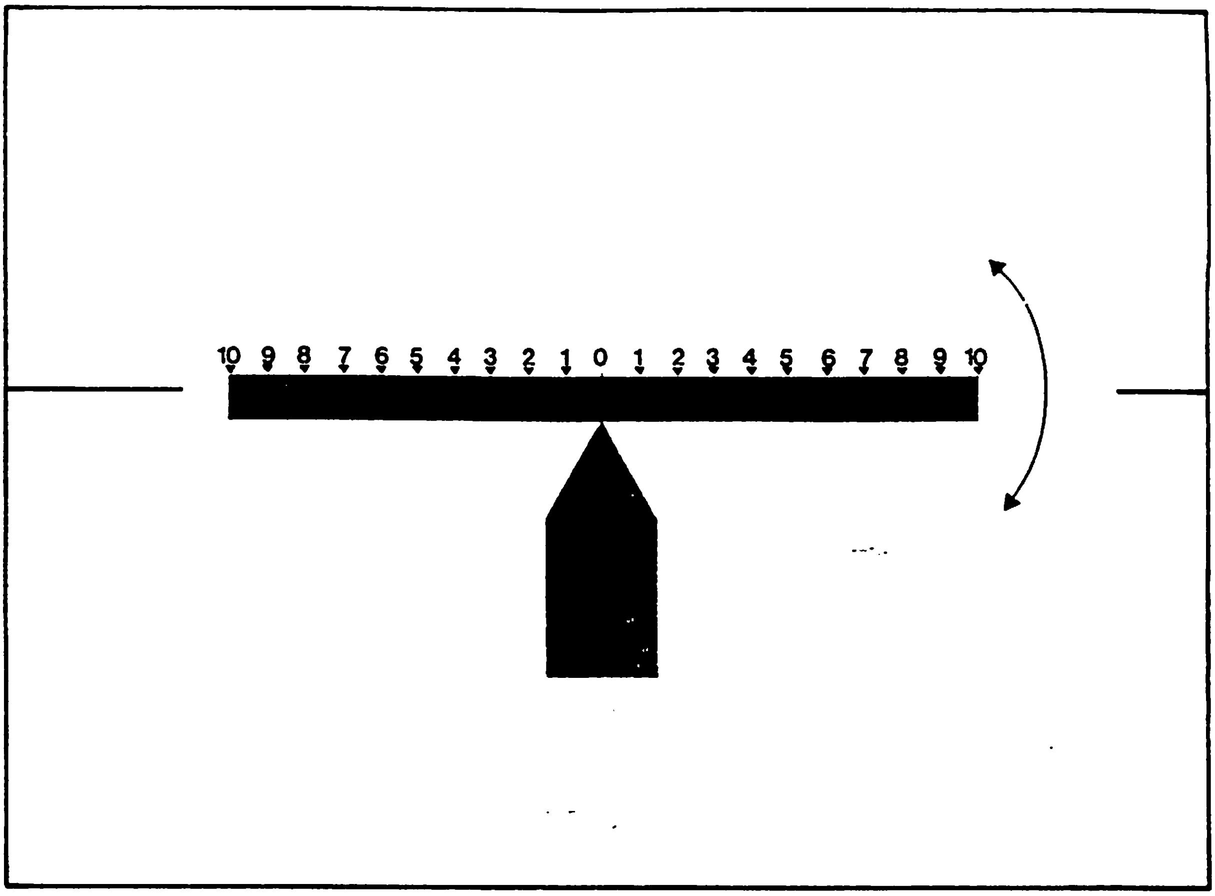
A small toy wind-up turtle is placed on a shaded strip of paper. The paper strip is lined up along the edge of a board as shown in the picture. The turtle can be moved along the paper strip. The paper strip can also be moved along the board. Both the toy and the paper strip can be moved forward or backward. The toy, the end of the paper strip, and the starting point on the board are all lined up as shown.

22 If the turtle moves forward at the same speed that the paper strip moves backward, how far will the turtle be from the starting point after a short time (as long as the turtle is still on the strip of paper)?

A. It would be at the starting point.
B. One-fourth the distance of the paper strip from the starting point.
C. Double the distance of the paper strip from the starting point.
D. It would be behind the starting point.

23 If the turtle moves forward at 1/3 the speed that the paper strip moves backward, where would the turtle be after a short period of time (as long as the turtle is still on the strip of paper)?

A. Three times as far forward as the paper strip is backward from the starting point.
B. One-third the distance in front of the starting point as the paper strip is behind the starting point.
C. It would be behind the starting point.
D. As far in front of the starting point as the end of the paper strip is in back of it.



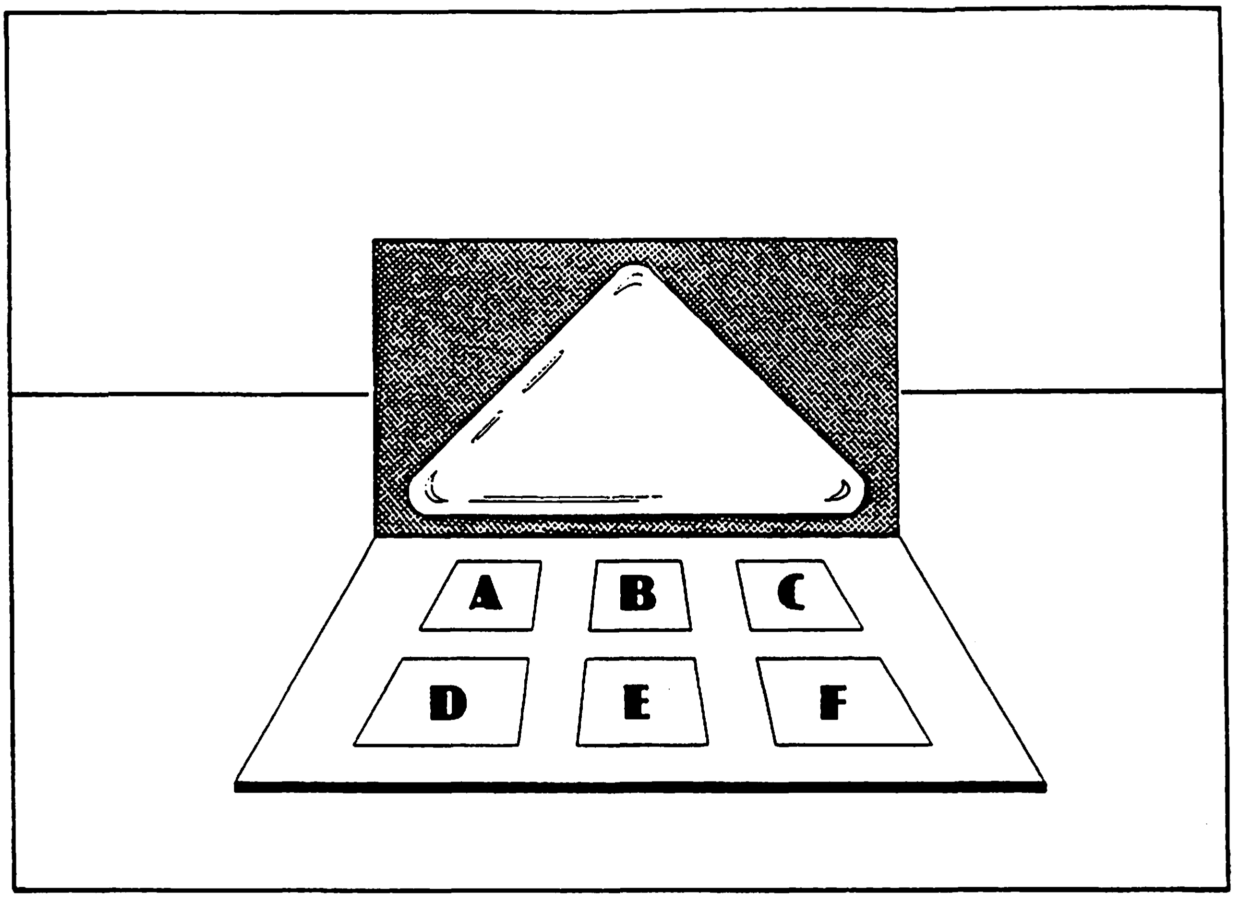
A group of children are playing in the park on a see-saw. When TWO children, each weighing approximately 20 kilograms each sit on the place marked 5 to the left of the balance point, the see-saw tips downward to the left. To balance the see-saw once again, two children, each weighing approximately 20 kilograms, have to sit on the right on the spot marked with a 5. The following questions refer to this see-saw and to the numbered places along it.

24 If THREE children each weighing approximately 20 kilograms each now sit on the place marked 5 to the left, where will the two children on the right have to sit to put the see-saw back into balance? (It is not necessary for these two children to sit at the same mark.)

A. The two children on the right can NOT balance the three children on the left.
B. Both children on the right will have to sit on the place marked 10.
C. One child should sit on the place marked 4 and the other child should sit on the place marked 6.
D. One child should sit on the place marked 7 and the other child should sit on the place marked 8.

25 If FOUR children each weighing approximately 20 kilograms each now sit on the place marked 5 to the left, where will the two children on the right have to sit to put the see-saw back into balance? (It is not necessary for these two children to sit at the same mark.)

A. The two children on the right should sit on the place marked 5.
B. The two children on the right should sit on the place marked 10.
C. One child should sit on the place marked 6 and the other child should sit on the place marked 9.
D. One child should sit on the place marked 8 and the other child should sit on the place marked 10.



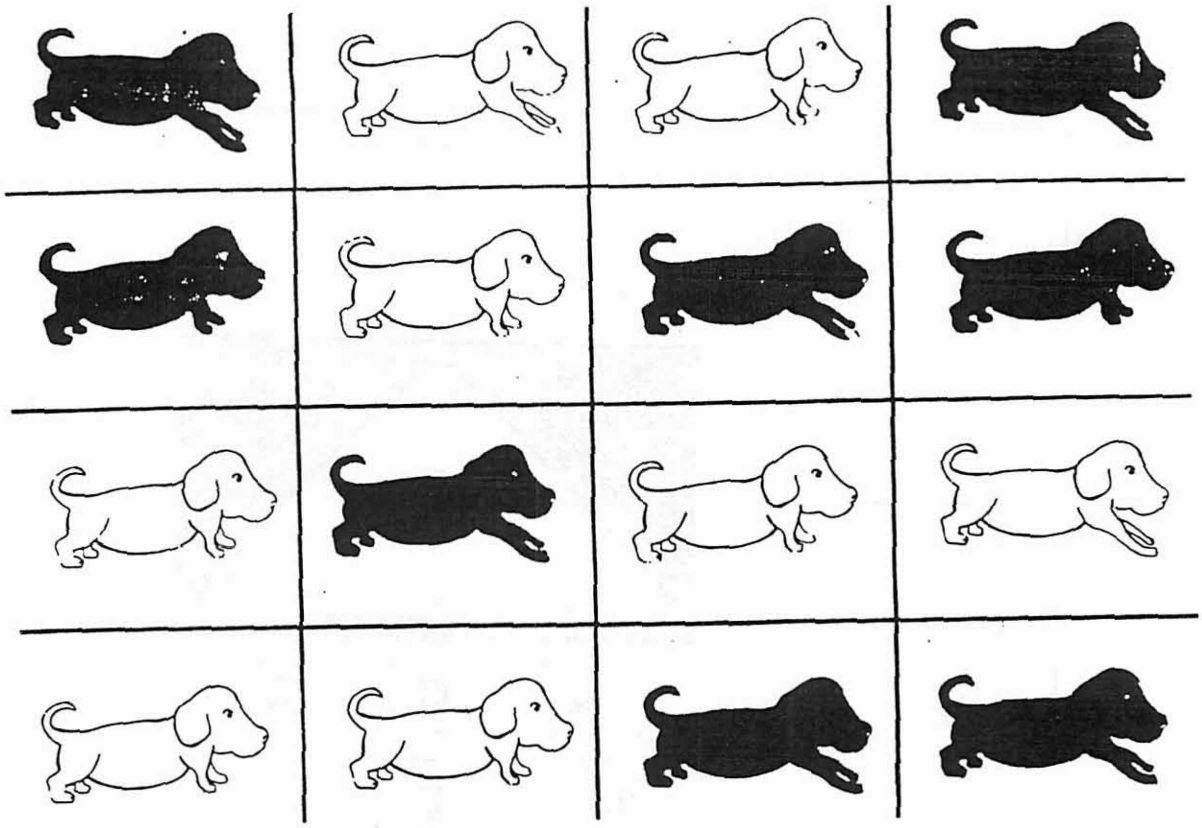
There is a new computer game in the stores. The object of the game is to light up the triangle at the top of the game board. The light goes on when one or more of these buttons are pressed down at the same time. These buttons are marked A to F. Pressing any wrong button will prevent the light from coming on.

26 How would you find out which of these buttons when pushed down at the same time will make the light go on?

A. Try all possible pairs of the buttons to make the light go on.
B. Try the buttons one-at-a-time and then two-at-a-time until the triangle lights up.
C. Try all six at a time and then all of the buttons taken five-at-a-time, four-at-a-time, and so forth, until the light goes on.
D. Try the bottons, six-at-a-time, five-at-a-time, four-at-a-time or three-at-a-time.

27 What is the reason for choosing your answer?

A. The problem requires that you test all combinations of the buttons from one-at-a-time to all six-at-a-time.
B. The word "combination" implies a pair, or two-at-a-time.
C. The information given in the problem requires that you test all combinations of the buttons taken three, four, five and six-at-a-time.
D. The problem can NOT be solved with the information that is provided even if you had the actual game and could work with it.



You are given a set of 16 cards. Each card has a picture of a hound dog which is either black or white in color, and who has either long or short legs. Card 1 represents a black dog with long legs. The following questions are to be answered on the basis of these 16 cards.

28 Can you find a relationship between body color and leg size for this type of dog, on the basis of these 16 cards?

A. No, because there is an even number of black and of white dogs with short legs.
B. No, because 8 dogs have short legs and 8 dogs have long legs and therefore there is no relationship.
C. Yes, because all of the black dogs have short legs.
D. Yes, because most of the black dogs have long legs and most of the white dogs have short legs.

29 What are the chances of a black dog having long legs based on the 16 cards above?

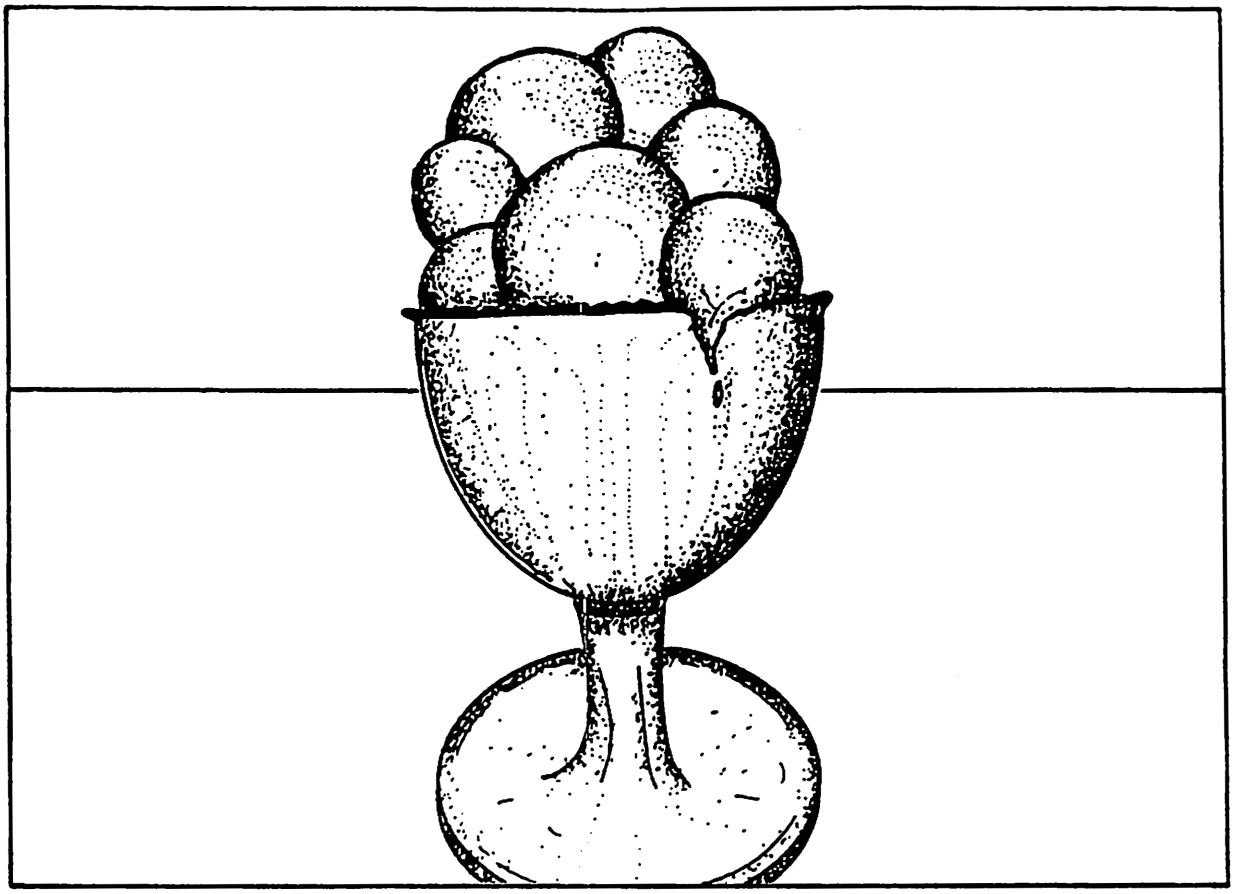
A. Six-out-of-eight
B. Four-out-of-eight
C. One-out-of-four
D. Nine-out-of-sixteen

30 What are the chances of a white dog having long legs based on these 16 cards?

A. One-out-of-six
B. One-out-of-eight
C. Two-out-of-eight
D. One-out-of sixteen

31 What are the chances of a black dog having short legs based on these 16 cards?

A. Two-out-of-eight
B. Three-out-of-eight
C. Three-out-of-sixteen
D. No chance at all



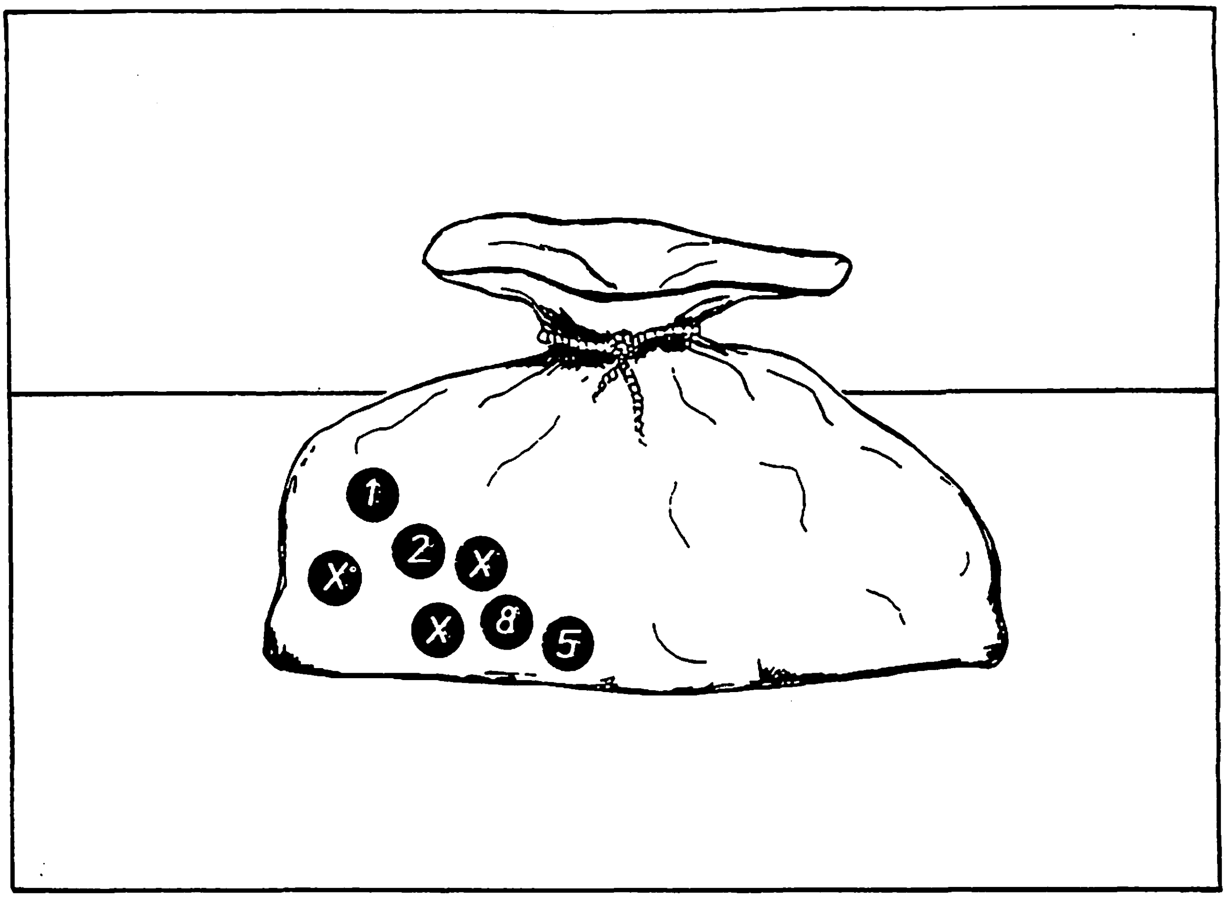
A local ice cream shop features a Do-It-Yourself-Sundae-Bar with five choices of toppings. The five toppings are: chocolate, fudge, strawberry, marshmallow and pineapple.

32 If you wanted to make a sundae using 3 different toppings, how many different kinds of sundaes could you prepare?

A. 5 types of sundaes
B. 8 types of sundaes
C. 10 types of sundaes
D. 15 types of sundaes

33 How many different types of sundaes, each with a different combination of toppings could you make using at least one topping on each sundae?

A. 31 different types
B. 15 different types
C. 10 different types
D. 50 different types



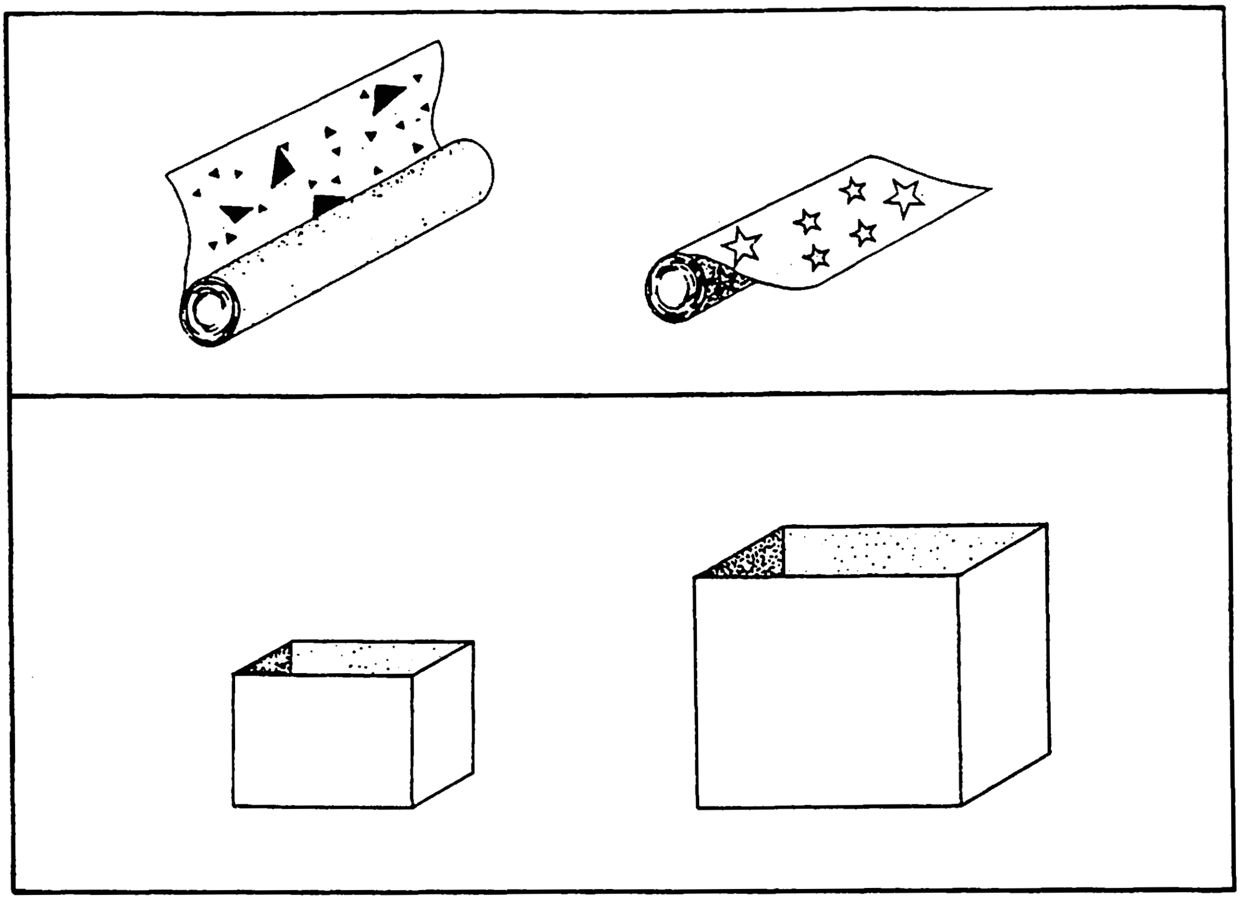
There is a game on a well-known TV quiz show that contestants play to win a new car. Seven tokens are placed in a cloth bag. Three tokens contain an X. If these three tokens are drawn from the bag before the four numbers in the price of the car, the contestant loses. If, however, the contestant draws the four numbered tokens before drawing the third token marked with an X, the contestant wins a new car. Each time a token is drawn it remains out of the bag. The following questions are based on this game.

34 If a contestant draws 3 numbered tokens and 1 token marked X, what are the chances of winning the car on the next draw?

A. Three-out-of-seven
B. Three-out-of-four
C. Two-out-of-three
D. One-out-of-three

35 What is the reason for your answer to this question?

A. There are three tokens without numbers that have to be taken into account.
B. Three of the numbered tokens have already been drawn and there are four numbered tokens in all.
C. Two of the remaining tokens contain X's out of the three possible tokens from which you can draw.
D. There is only one numbered token that remains out of the total.



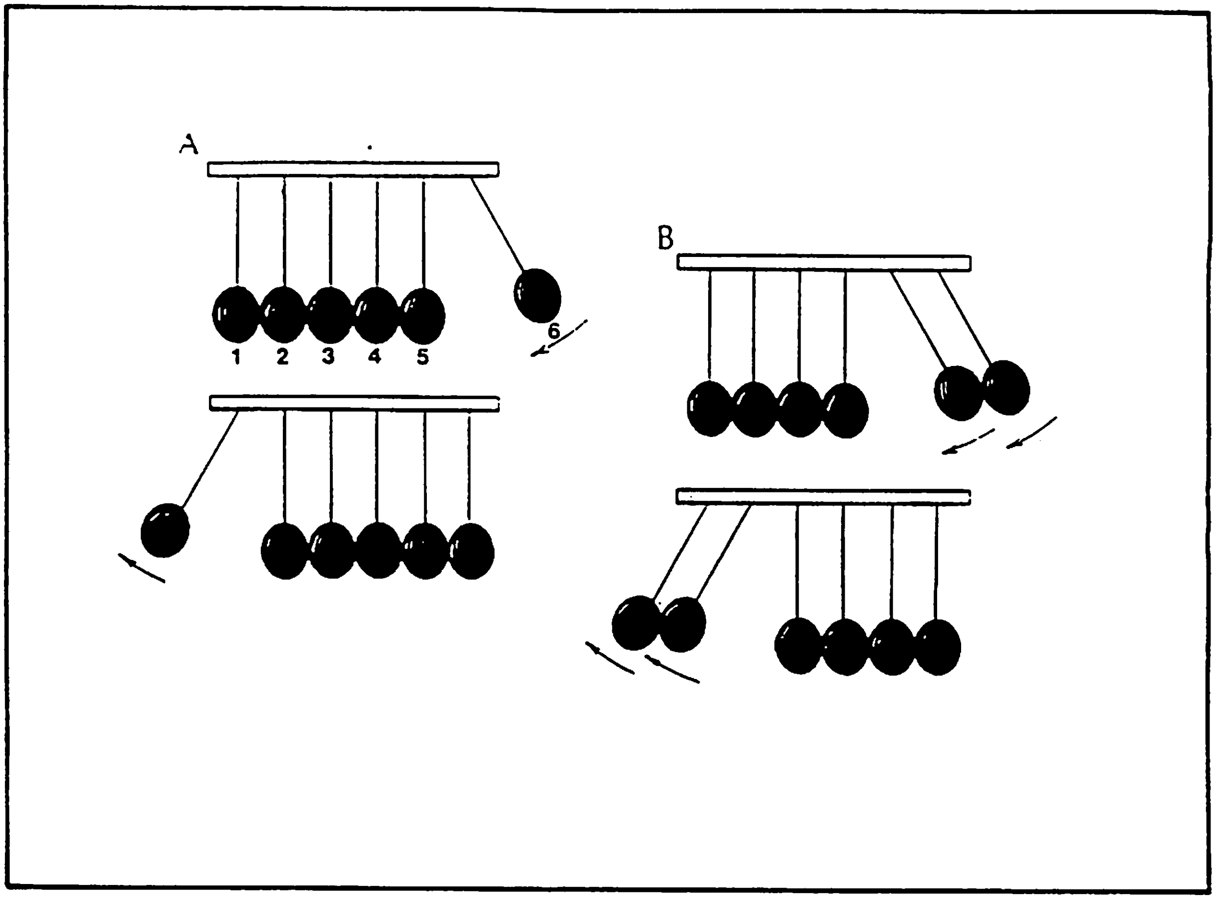
Two rolls of gift paper are to be used to wrap presents. One has a star pattern and one has a triangle pattern. One present will go into the large box pictured above and one will go into the small box. It takes 6 widths of the star paper to cover the small box and 8 widths of the star paper to cover the large box. When the triangle pattern paper is used, it takes 9 widths of this paper to cover the smaller box.

36 Without first wrapping the larger box, how many widths of the triangle paper are needed to cover the larger box?

A. 12 widths
B. 11 widths
C. 10 widths
D. 18 widths

37 Why would you need the number of widths that you chose?

A. The difference between 6 widths and 8 widths is 2 widths. You have to add these 2 widths.
B. The star paper's width is 3/2 the triangle paper's width, so you need 3/2 of 8 widths.
C. The difference between 6 widths and 8 widths is 2. You have to multiply the 9 widths by this difference.
D. The star paper's width is 4/5 the triangle paper's width, so you need 4/5 as much.



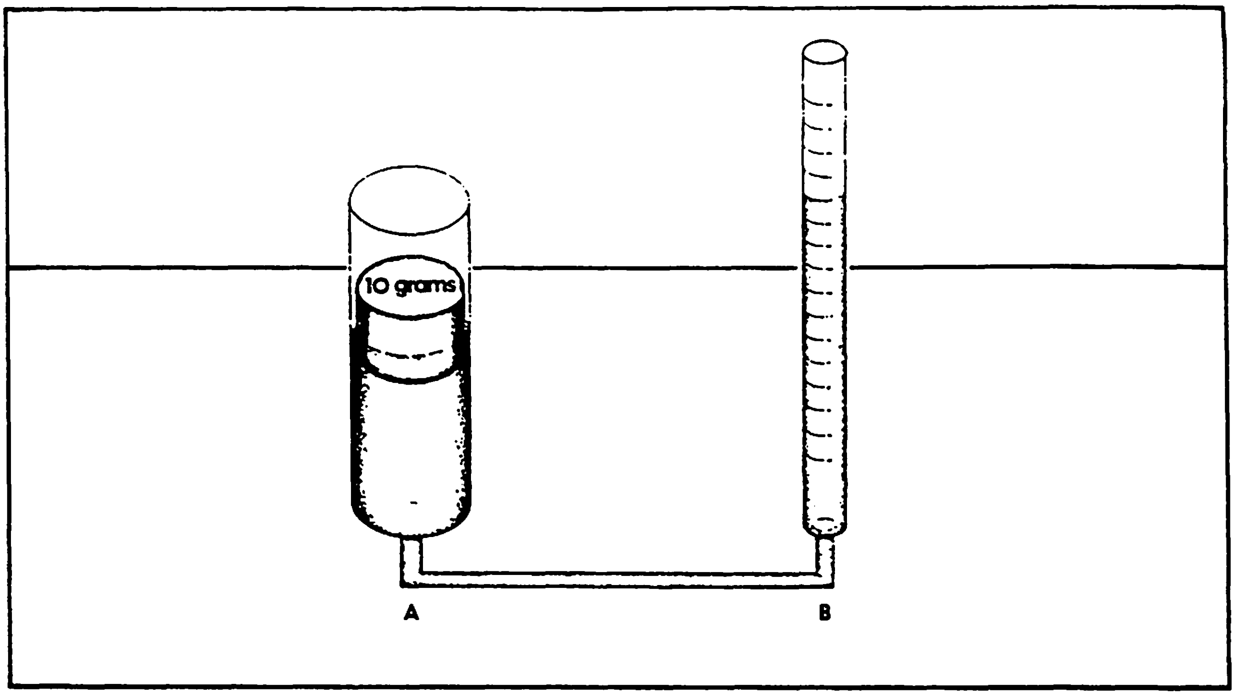
A few years ago there were several games in department stores which were for business executives, to calm their nerves. One such game is pictured above. Six plastic balls are hung from a support bar. When the ball marked 6 is pulled back and then let go, it swings forward and hits ball 5. When this happens, ball 1 swings forward and back while the balls numbered 2-6 do not move. If balls 5 and 6 are pulled back and then let go, balls 1 and 2 swing forward and back. Balls 3 and 4 do not move.

38 If balls 3, 4, 5, and 6 are pulled back and then let go, which balls will swing out?

A. Balls 1, 2
B. Balls 1, 2, 3
C. Balls 1, 2, 3, 4
D. Balls 1, 2, 3, 4, 5, 6

39 What is the reason for your answer to the question above?

A. Only the balls that were not pulled back would swing out.
B. Balls 4, 5, 6 would transfer their energy to ball 3 which would swing out and push out balls 1 and 2 in front of it.
C. All would swing out because more balls are pulled back than are left to be hit.
D. Since only four balls were pulled back and then let go, only that number would swing out.



When weights are placed on the top of the water in jar A, the weights push down on the water and force the water up the thin glass pipe B. The greater the weight on A, the higher the column of water in B.

40 If the weight on A is doubled, what will happen to the height of the column of water in B?

A. It will go up to a height 50 percent greater than before.
B. It will go up twice the height of before.
C. It will stay the same.
D. It will be lower by one-half the height.

41 The water is replaced by a liquid that is more dense than water. What will happen to the height of the column of liquid in B if the same weight is applied to A as in the question above?

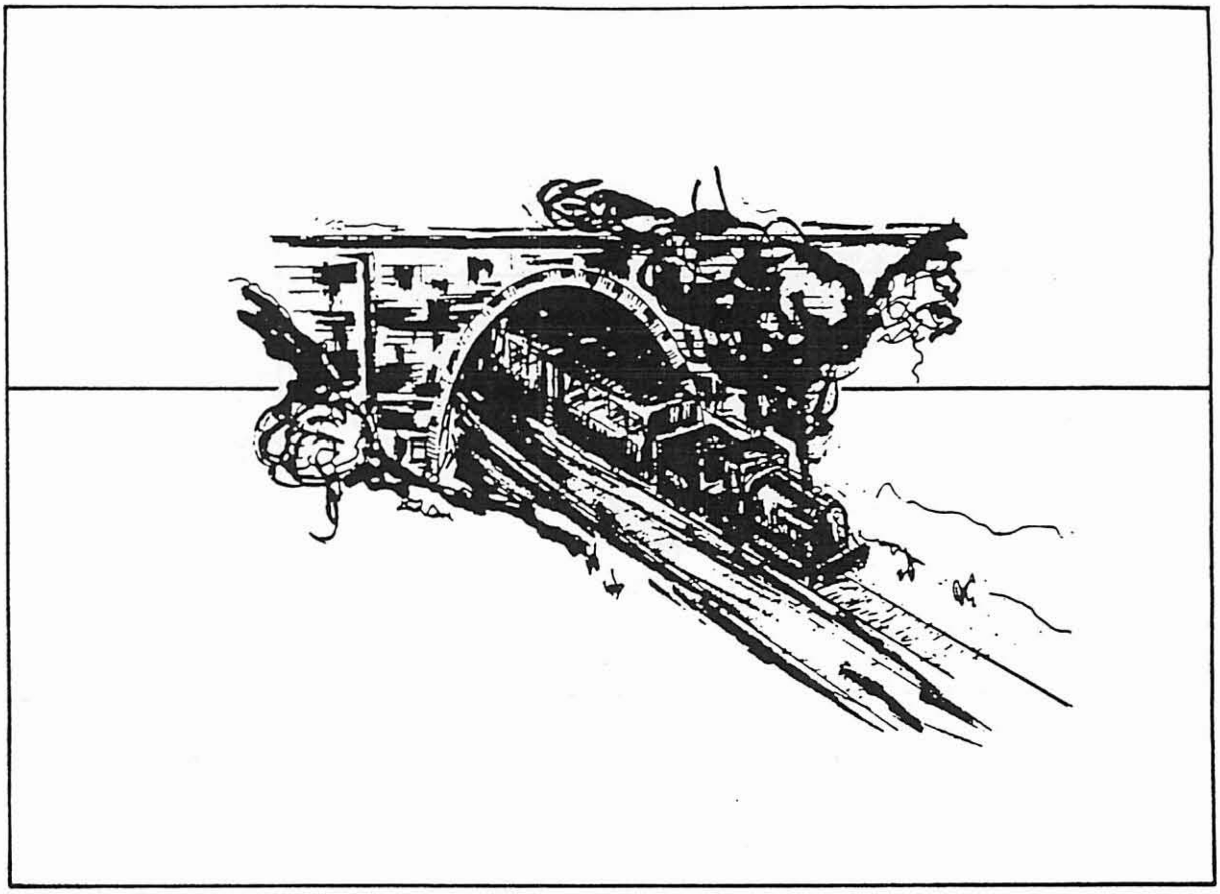
A. It will go up to a height 50 percent greater than in the previous question.
B. It will go up higher than in the previous question.
C. It will be lower than the level it achieved in the previous question.
D. It will go up to the same height as in the previous question.

42 What is the reason for your answer to the question just above (the second question)?

A. The liquid is denser, so more weight will be required to push it up to the same level.
B. The liquid will always go to the top no matter how hard the weight pushes on the liquid.
C. The type of liquid does not affect how far the column will rise. Only the weight affects this.
D. The liquid is denser and so the column will rise higher.

43 The weight on the denser liquid is now four times what it was originally. What will happen to the column of liquid in B?

A. It will go up to a height double that in the second question.
B. It will go up four times as high as it did in the second question.
C. It will go to the same height as it did in the second question.
D. The additional weight will NOT affect the height of the column in B.



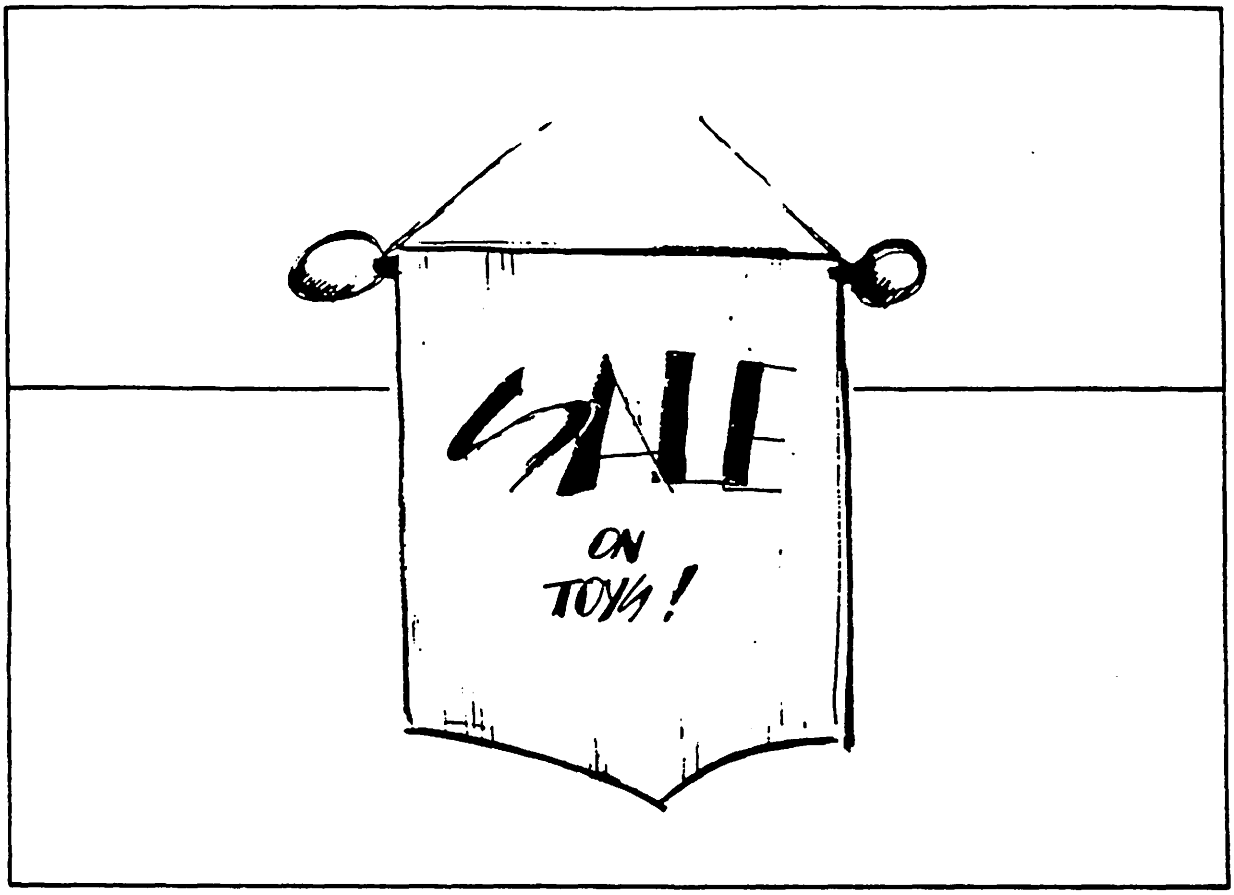
Two people are sitting on this train as it passes through a long tunnel in the side of a mountain. Mr. Red (R) is sitting at the front of the train and Mr. Blue (B) is sitting at the back of the train. For the following two situations, decide whether Mr. R and Mr. B will stay in the tunnel for the same amount of time.

44 SITUATION 1: After the train enters the tunnel Mr. R gets up from his seat in the front, and walks back to sit with Mr. B. How much time altogether will Mr. R spend in the tunnel?

A. Less time in the tunnel than Mr. B.
B. Twice the time in the tunnel as Mr. B.
C. The same amount of time in the tunnel as Mr. B.
D. More time in the tunnel than Mr. B.

45 SITUATION 2: After the train has entered the tunnel, Mr. B gets up from his seat in the back. He walks forward to sit with Mr. R. Halfway on his trip forward, he decides to go back to his seat for his paper. He gets his paper and then goes forward again and joins Mr. R, while the train is still in the tunnel. How much time did Mr. B spend in the tunnel?

A. Less time in the tunnel than Mr. R.
B. More time in the tunnel than Mr. R.
C. One-and-one-half as much time in the tunnel as Mr. R.
D. The same amount of time in the tunnel as Mr. R.



A local toy manufacturer explained to one of his friends that no matter what he charges, the quantity he sells always goes up and down in relation to that price. The result is that the total revenue (money he takes in) is constant (remains the same). For example, if he raises his price, his sales decrease just enough so that the revenue is kept constant. Just the opposite happens if he lowers his price. His present cost per toy is constant no matter how many toys he produces. He wants to know how he should change the way he runs his toy business so that he can make the most profit.

46 What can he do to make the most profit?

A. There is nothing he can do because the total revenue remains constant.
B. Pick a price that is right in the middle so demand is high but he can meet the demand.
C. Increase the quantity of toys sold.
D. Reduce the cost of producing the toys.

47 If the toy manufacturer were to double the number of toys that he made with no change in his cost per toy, what would happen to his profit?

A. It would be cut in half.
B. It would remain the same.
C. It would double.
D. It would be four times as great.

Activity 7: Scaling: pictures and microscopes

Introduction

This lesson puts scaling into a biological context and reinforces the calculation of ratios. Diagrams of human embryos are used to illustrate 'scaling up' and 'scaling down'. Pupils use a microscope and see magnification as a scaling up process.

For the second part, pupils need to have had experience with microscopes. If they have not, you could either put in a special lesson introducing microscopes before this activity or use the first part on scaling drawings, and extend it with examples from text books etc. Then construct a fuller lesson which both introduces the use of microscopes, and deals with the scaling aspects outlined in the second part of this intervention lesson. This uses the idea of ratio, introduced in the last lesson, and the notion of 'scaled up' or 'scaled down' provides some cognitive conflict.

Apparatus summary

Per group

- Microscope, slides and coverslips, forceps
- Transparent ruler or graph paper sellotaped t slide

Per pupil

- Worksheet
- Workcard A
- Workcard B

Procedure summary

1 Discuss the need to reduce or enlarge drawing photographs etc.

2 Pupils assess whether drawings of embryos ha been scaled up or scaled down, and by how much (first three columns of the first table on the Worksheet). Use the word **ratio.**

3 The magnifying power of the microscope: Tot power = power of eyepiece × power of objective.

4 Pupils 'guesstimate' the diameter of a hair, us a transparent ruler (or a slide with graph paper) under the microscope.

Procedure details

1 *(5 minutes)* Scale drawings. Discuss the need to reduce or enlarge drawings, photographs, etc., to fit on a page or to show detail. This is particularly important for many biological drawings and photographs.

2 *(20 minutes)* On the drawings of the human embryos, **a** and **b** are still in the womb and **c** is just born i.e. has had nine months development. Pupils are asked to assess if each drawing has been 'scaled up' or 'scaled down' i.e. are they larger or smaller than life? How could one calculate how much bigger or smaller the drawings are compared with the real embryos? Pupils measure the length of each drawing (lines a,b,c.) and fill in the first three columns of the first table on the Worksheet. Illustrate the first calculation using the word **ratio.** Pupils should then continue to complete the table on their own.

Age of embryo	Drawing/Real size	Scale
6 weeks	60/12	× 5
3 months	135/45	× 3
9 months	90/360	× 1/4

The last one is difficult. It helps to ask 'is the drawing bigger or smaller than a real baby?', and 'what would you have to multiply the size of the real thing by to get the drawing?'

3 *(10 minutes)* The magnifying power of the microscope. Explain that **magnification** is like scaling up so that small things look big. The tota **magnifying power** of a microscope is the magnification of the eyepiece multiplied by that of the objective. This is really bridging the scaling id to regular use of the microscope.

4 *(15 minutes)* Pupils use a transparent ruler (o slide with graph paper) to measure the diameter the field of view (Workcard section 3). Then the width of a hair can be estimated from the proportion of the field of view occupied. The exercise is intended to give the pupils a feel for magnification.

5 *(20 minutes or homework)* Workcard B has problems on scaling.

Answers to numerical questions

1a Scaled up
1b About four times
1d ×4
2 ×60, ×100, ×240, ×400
3 About 3.5 mm

Activity 7: Worksheet

Proportionality

Scaling: pictures and microscopes

1 Scale drawing

a None of the human embryos is drawn 'life-size.' Why not?

....

b Each drawing is to **scale**. Compare the real life-size length of each embryo with the size of the drawing.

Which drawings have been **scaled up** (made larger than life)?

Which drawings have been **scaled down** (made smaller than life)?

c Measure the lengths of each drawing (lines a, b, c). Write them in the table. Now write the real-life lengths in the table.

The **scale** is the ratio of the drawing size to the real size. Work it out and complete the table.

Age of embryo	Drawing size (mm)	Real size (mm)	Ratio drawing/real	Scale
6 weeks				×
3 months				×
9 months				×

2 and 3 Microscope magnification

	Magnifying power of eyepiece (1)	Magnifying power of objective (2)	Total magnification (1) × (2)	Width of field of view
Low power				
High power				

4 Hair

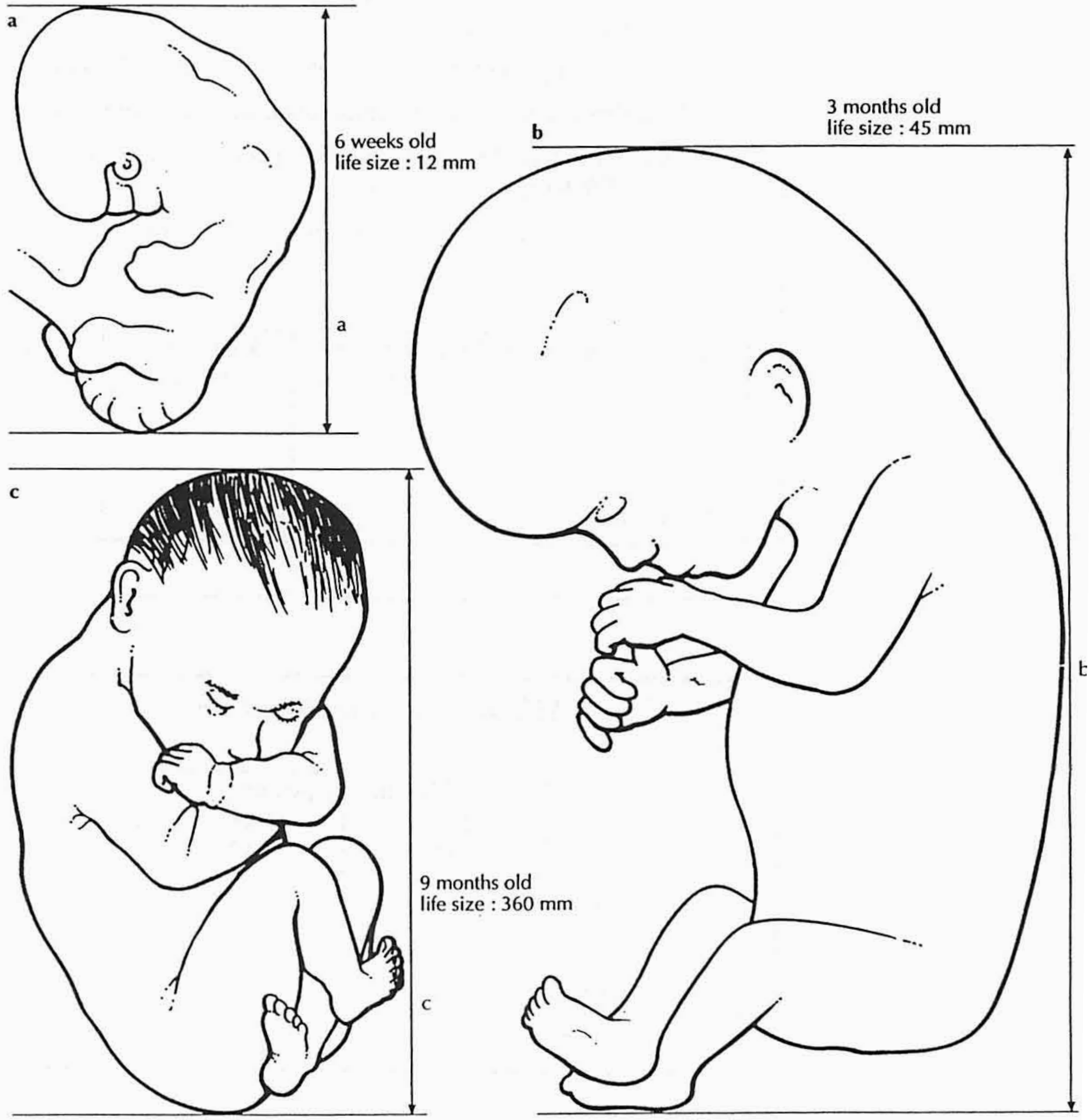
Approximate width of hair: .... mm

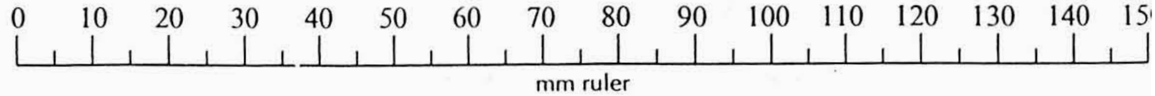
Activity 7: Workcard A *Proportionality*

Scaling: pictures and microscopes

1 Scale drawings

Human embryos at different ages.
All drawings are to scale.





mm ruler

Activity 9: Trunks and twigs

Compensation

Introduction

A qualitative introduction to the idea of compensation – one variable increasing in value as another decreases. The idea of compensation runs through much scientific work including the more difficult conservation problems (a clay block remains the same volume when its shape changes: increase in thickness compensated for by decrease in length, etc.). As a field exercise this is a genuine bit of research, since the outcome is not known to pupils, teachers, nor to anyone else!

Apparatus summary

Groups of three are ideal for this.

Per group

- A 'diameter measurer' (see Technician's Guide)
- One Workcard (covered in plastic if possible) per group

Per pupil

- Worksheet (and something to press on)

Identify in advance bushes near the school which are suitable.

If it is impossible to take the pupils out to measure bushes, you could, as a last resort, use copies of drawings (which pupils can measure in mm instead of cm).

Procedure summary

1 Give out the Workcards, and go through the first couple of paragraphs. Introduce the word **compensation**. There is no 'right' answer to this exercise, it is a genuine investigation into a relationship between branch thickness and distance from ground.

2 Demonstrate how to use the card gauge.

3 Check that all pupils know how to count up the number of joints.

4 Take the class out and point out suitable bushes.

5 Pupils plot graphs.

6 For pupils, the important thing is that with compensation relationships the line slopes backwards.

Procedure details

1 *(15 minutes for 1, 2 and 3)* Go through the first couple of paragraphs of the Workcards, emphasising the variables to be measured. Make it clear that as you go higher up a tree, the branches get thinner – as distance up increases, branch diameter decreases. 'One goes down as the other goes up.' This can be described as **compensation**.

Make the point that there is no 'right' answer to this exercise, it is a genuine investigation into a relationship between branch thickness and number of joints for the particular bushes around your school.

2 Demonstrate how to use the card gauge.

3 Go over the picture of the bush on the Workcard or OHP, ensuring that all pupils are clear how to count up the number of joints between the branch they are measuring and the ground, or the main branch or trunk.

4 *(15 minutes)* Lead the class out to an area of bushes already identified, and point out one or two suitable ones as examples. You will probably be kept quite busy answering questions such as 'do we count this as a joint?', and 'whereabouts exactly should we measure?'. Frankly, your answers are not very important, as long as they are consistent.

5 *(15 minutes)* When everyone has sets of measurements on at least two bushes, return to the class. By now, many pupils will have the idea that in order to investigate a relationship, it is a good idea to draw a graph. Maybe someone can predict what direction the graph will go for this compensation, one up–one down, sort of relationship.

They will have to make their own vertical scale, according to the thickest branch that they have measured. When measuring living things, there is a lot of random variation, so it is legitimate to draw a 'best fit' straight line along points nearly on a straight line. Points for the two or three different bushes can be plotted in the same space, using different colours.

6 *(10 minutes)* Lead a discussion about the relationship that emerges: the important thing is that this is a case of compensation. As the number of joints goes up thickness goes down. The line, whether straight or not, slopes backwards.

There may be other interesting observations, such as if a branch has been cut, it tends to thicken with the effect that the straight line curves to flat at the end.

Any time available at the end can be used for bridging discussion of other situations where there are compensation relationships.

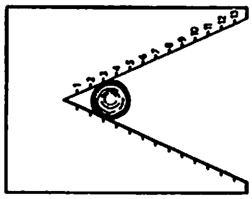
Activity 9: Workcard (diameter gauge) *Compensati*
Trunks and twigs

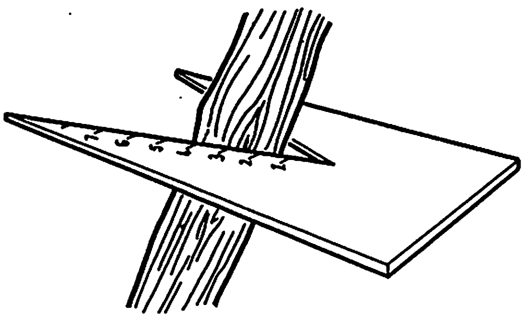
The higher up a tree you go, the thinner the branches become.

But what exactly is the relationship between:

- the thickness of a branch, and
- the number of times it has branched from the ground?

You can find out by measuring some bushes.





How to measure the thickness of a branch

Use the special gauge.

Push the gauge gently around the branch. Read the diameter from the mark that touches the branch.

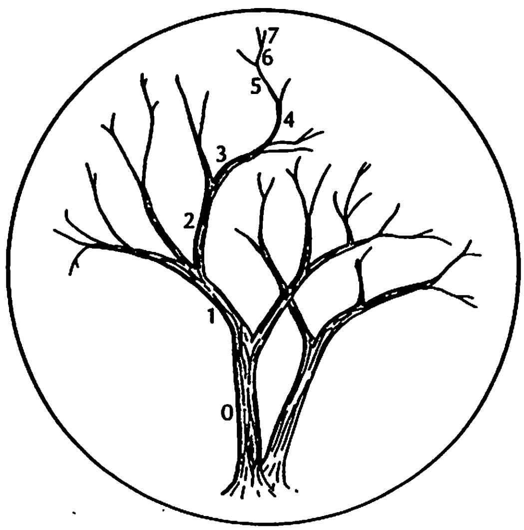
If the branch is not really round, measure across the thinner direction.

How to count joints

Look at the picture of a bush. Where the 0 is written there are *no* joints between the branch and the ground.

Where the number 1 is written, there is one joint between the branch and the ground, and so on.

(If there is a tiny twig coming off a branch, do *not* count this as a joint.)

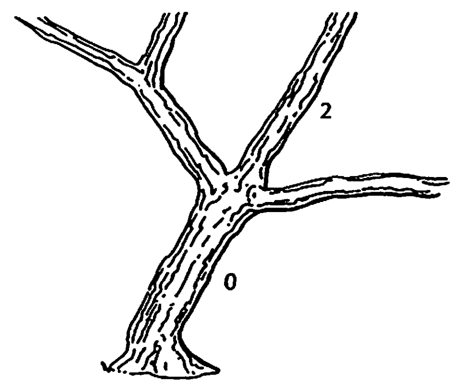


What to do

1 Find a bush which has quite a lot of branching. Start with the trunk (or one of the trunks) coming from the ground. Measure its thickness, and write this next to the 0 in the table on the Worksheet.

2 Now follow that branch up, just past the first joint. Choose the larger of the two branches after the joint. Measure its thickness and record it in the table next to the 1.

If two branches come off at once, like this, you cannot get a measurement at '1 joint up'.
Go straight to '2 joints up'.



3 Carry on as far as you can go, until you cannot reach, or you reach the top of the bush, or you have gone beyond eight joints.

4 Do the same thing again with a different bush. If you have time, repeat with a third bush.

APENDIX 3
ACHIEVEMENT TESTS

Part B: Comprehension of Evolution (15 marks)

For questions 1 to 5, use the numbered statements listed below and circle the number which most closely corresponds to what you understand. **Explain your answer with a few sentences.**

Scale
1. The statement to the left is the only correct statement.
2. Both statements are correct but the statement on the left is more correct.
3. Both statements are equally correct.
4. Both statements are correct but the statement on the right is more correct.
5. The statement to the right is the only correct statement.

1. In the tropics there is a **small** population of moths in which two types coexist. The dominant allele produces wings of a solid colour; while, the recessive allele produces striped wings. Biologists show that there is no selective advantage in the tropics for one wing pattern over the other.

The wing pattern will **not** evolve because there is no selective advantage.	1 2 3 4 5	The wing pattern will evolve because genetic drift will change the allelic frequencies over time

Explain your answer.

2. Ducks are aquatic birds Their feet are webbed and this genetic trait makes them fast swimmers. Biologists believe that ducks evolved from land birds which did not have webbed feet. The trait in of web feet in ducks

Appeared in ancestral ducks because they lived in water and needed webbed feet to swim	1 2 3 4 5	Appeared in ancestral ducks because of a chance mutation

Explain your answer.

3. While ducks were evolving webbed feet

With each generation, most ducks were similar to their parents and had about the same mount of webbing on their feet; a few ducks had more webbibg.	1 2 3 4 5	With each generation, most ducks had more webbing on their feet than their parents.

Explain your answer.

4. If a population of ducks were forced to live in an environment were water for swimming was no available

Many ducks would die because their feet were poorly adapted to this environment.	1 2 3 4 5	Many ducks would gradually develop webbed feet.

Explain your answer.

5. Allopatric speciation was responsible for the new species of ducks with webbed feet

because these ducks doubled the chromosome number and could no longer breed with the ancestral ducks.	1 2 3 4 5	because these ducks always remained in water while the ancestral ducks always remained on land

Explain your answer.

6. Write a short essay (1 or 2 paragraphs) on **ONE** of the following topics.
   A. What is the role and influence of meiosis on genetics and genetics on evolution.
   B. Compare (and give examples) of the influence of adaptive and non-adaptive selection on evolution.
   C. Describe the ways in which two species remain distinct.

31. Suppose there is a large beaker full of clear water and a drop of blue dye is added to the beaker of water. Eventually the water will turn a light blue color. The process responsible for blue dye becoming evenly distributed throughout the water is:

    1. osmosis
    2. diffusion
    3. a reaction between water and dye

32. The reason for my answer is because:

    1. the lack of a membrane means that osmosis and diffusion cannot occur
    2. there is movement of particles between regions of different concentrations
    3. the dye separates into small particles and mixes with water
    4. the water moves from one region to another

33. During the process of diffusion, particles will generally move from:

    1. high to low concentrations
    2. low to high concentrations

34. The reason for my answer is because:

    1. there are too many particles crowded into one area; therefore, they move to an area with more room.
    2. particles in areas of greater concentration are more likely to bounce toward other areas.
    3. the particles tend to move until the two areas are isotonic, and then the particles stop moving.
    4. there is a greater chance of the particles repelling each other.

35. As the difference in concentration between two areas increases, the rate of diffusion:

    1. decreases
    2. increases

36. The reason for my answer is because:

    1. there is less room for the particles to move.
    2. if the concentration is high enough, the particles will spread less and the rate will be slowed.
    3. the molecules want to spread out.
    4. there is a greater likelihood of random motion into other regions.

37. A glucose solution can be made more concentrated by:

1. adding more water
2. adding more glucose

38. The reason for my answer is because:

1. the more water there is, the more glucose it will take to saturate the solution.
2. concentration means the dissolving of something.
3. it increases the number of dissolved particles.
4. for a solution to be more concentrated one must add more liquid.

39. If a small amount of sugar is added to a container of water and allowed to set for a very long period of time without stirring, the sugar molecules will:

1. be more concentrated on the bottom of the container
2. be evenly distributed throughout the container

40. The reason for my answer is because:

1. there is movement of particles from a high to low concentration.
2. the sugar is heavier than water and will sink.
3. sugar dissolves poorly or not at all in water.
4. there will be more time for settling.

41. Suppose you add a drop of blue dye to a container of clear water and after several hours the entire container turns light blue. At this time, the molecules of dye:

1. have stopped moving
2. continue to move around randomly

42. The reason for my answer is because:

1. the entire container is the same color; if they were still moving, the container would be different shades of blue.
2. if the dye molecules stopped, they would settle to the bottom of the container.
3. molecules are always moving.
4. this is a liquid; if it were solid, the molecules would stop moving.

43. Suppose there are two large beakers with equal amounts of clear water at two different temperatures; Beaker 1 is at 5 degrees centigrade while Beaker 2 is at 20 degrees. . Next, a drop of green dye is added to each beaker of water. Eventually the water turns light green. Which beaker became light green first?

1. Beaker 1
2. Beaker 2

44. The reason for my answer is because:

1. the lower temperature breaks down the dye.
2. the dye molecules move faster at higher temperatures.
3. the cold temperature speeds up the molecules.
4. it helps the molecules to expand.

45. Two columns of water are separated by a membrane through which only water can pass. Column 1 contains dye and water; column 2 contains pure water. After 2 hours, the water level in column 1 will be:

1. higher
2. lower
3. the same height

46. The reason for my answer is because:

1. water will move from the hypertonic to hypotonic solution.
2. the concentration of water molecules is less on side 1.
3. water will become isotonic.
4. water moves from low to high concentration.

47. In question 45, column 1 is ____________ to column 2.

1. hypotonic
2. hypertonic
3. isotonic

48. The reason for my answer is because:

1. water is hypertonic to most things.
2. isotonic means "the same".
3. water moves from a high to a low concentration.
4. there are fewer dissolved particles on side 1.

49. If a plant cell that lives in freshwater were placed in a beaker of 25% saltwater solution, the central vacuole would:

1. increase in size
2. decrease in size
3. remain the same size

50. The reason for my answer is because:

1. salt absorbs the water from the central vacuole.
2. water will move from the vacuole to the saltwater solution.
3. the salt will enter the vacuole.
4. salt solution outside the cell cannot affect the vacuole inside the cell.

51. Suppose you killed the plant cell with poison and placed the dead cell in a 25% saltwater solution.

1. Osmosis and diffusion would not occur
2. Osmosis and diffusion would continue
3. Only diffusion would continue
4. Only osmosis would continue

52. The reason for my answer is because:

1. the cell would stop functioning.
2. the cell does not have to be alive.
3. osmosis is not random, whereas diffusion is a random process.
4. osmosis and diffusion require cell energy.

53. All cell membranes are:

1. semipermeable
2. permeable

54. The reason for my answer is because

1. They allow some substances to pass.
2. They allow some substances to enter, but they prevent any substances from leaving.
3. The membrane requires nutrients to live.
4. They allow ALL nutrients to pass.

55. What would you see if you could take one molecule of a sample of tap water and look at it under a microscope that allowed you to see every detail of this single water molecule?

1. A closed figure with no definite shape.
2. Two or more solid spheres.
3. A triangular shapped cloud.
4. A sphere with particles spread throughout.

56. Water is a/an

1. molecule
2. atom
3. element
4. neutron
5. electron

57. Would a sample of ice have the same structure under the microscope?

1. It would look exactly the same.
2. It would look exactly the same, except each "ice particle" would be closer.
3. It would look exactly the same, except each "ice particle" would be further apart.
4. It would look different.

58. Would a sample of steam have the same structure under the microscope?

1. It would look exactly the same.
2. It would look exactly the same, except each "steam particle" would be closer.
3. It would look exactly the same, except each "steam particle" would be further apart.
4. It would look different.

59. What element(s) make(s) up water molecules?

1. Oxygen, hydrogen and sodium.
2. Oxygen and hydrogen.
3. Hydrogen alone
4. Different forms of water are made up of different things (i.e., ice is not the same as steam or liquid water).

60. Which of the following statements is true?

1. All atoms contain the same number of molecules.
2. Different atoms are made up of different number of molecules.
3. Different molecules are made up of different number of atoms.
4. All molecules contain the same number of atoms.

61. There are _______ atoms in a tap water molecule.

1. one
2. two
3. three
4. tap water is not pure; therefore one cannot determine the number of atoms in the water molecule.

62. Which of the following statements is true?

1. All forms of water (liquid, ice, steam) are made up of the same number and type of of atoms.
2 Different forms of water contain a different number of atoms.
3. Different forms of water contain different types of atoms.
4. Differtent forms of water contain the same elements but in a different proportion.

63. What size is a molecule of water?

1. Water molecules always take the size of the container holding the sample of water.
2. About the size of a virus.
3. Water molecules come in different sizes.
4. Molecules are much smaller than even the smallest protein.

64. Which of the following statements is true?

1. All water molecules (ice, steam, liquid) are the same size.
2. Water molecules are not a fixed size, the size depends on environmental conditions.
3. The size of water molecules depends on the phase in question. All ice water molecules are the same size but they differ from steam molecules.
4. Molecules in the same form of water can have a different number of molecules..

65. Which statement is true?

1. An atom is flat but a molecule is a three-dimensional structure.
2. A molecule is flat but an atom is a three-dimensional structure.
3. Molecules and atoms are three dimensional structures.
4. Both molecules and atoms are flat.

66. Which statement is true?

1. All water molecules (ice, steam, liquid) have the same shape.
2. Water molecules do not have a fixed shape, the shape depends on environmental conditions.
3. The shape of water molecules depends on the phase in question. All ice water molecules have the same shape but they differ from steam molecules.
4. Molecules in the same form of water can be different shapes.

67. Which water molecules are the largest?

1. Ice, steam and liquid water molecules are all the same size.
2. Ice molecules.
3. Liquid water molecules.
4. Steam molecules.

68. Why did you choose your answer in 67 above?

1. Heat causes molecules to expand and get bigger.
2. Cold causes molecules to expand and get bigger.
3. Liquid water molecules are the most common so they must also be the biggest.
4. Since all molecules of water are made up of the same elements they are always the same size.

69. Which statement is true?

1. All water molecules weigh the same regardless of the form.
2. Ice molecules are the heaviest water molecules.
3. Liquid water molecules are the heaviest water molecules.
4. Steam molecules are the heaviest water molecules.

70. Which statement is true?

1. All water molecules have space between the molecules.
2. Only liquid water and steam have space between the molecules.
3. When ice melts the molecules expand and take up more space.
4. When ice melts the molecules shrink and space between the molecules is created .

71. In which form of water do the molecules move fastest?

1. Ice.
2. Liquid water.
3. Steam.
4. The molecules of water move at the same speed regardless of form.

72. Why did you choose your answer to 23 above.

1. Since all water molecules weigh the same they move with the same speed.
2. Steam molecules have more kinetic energy so they move fastest.
3. Cold molecules move fastest in an attempt to gain kinetic energy.
4. Water flows whereas ice and steam don't so its molecules must move faster.

73. Which statement is true?

1. Bigger molecules move slower than smaller ones.
2. A molecule in a large container will move faster than a molecule in a small container.
3. The speed of a molecule depends on its kinetic energy.
4. Heat causes molecules to expand. This, in turn, causes molecules to move faster.

74. Which statement about atoms is correct?

1. Atoms are flat.
2. Atoms are spheres with particles embedded in them.
3. An atom consists of a central nucleus with electrons moving in a fixed path around the nucleus.
4. An atom consists of a central nucleus with electrons moving in an undermined path around the nucleus.

75 The mass of an atom

1. Is always the same regardless of the element.
2. Is undeterminable.
3. Is different for different elements.
4. Changes with temperature and pressure.

76. Which statement is true?

1. The atoms in my body are alive but the atoms in my pen are not.
2. All atoms are alive.
3. Atoms are only alive if they move.
4. No atoms are alive.

77. Which statement is true?

1. A compound always cqnsists of different elements bonded together.
2. A compound can be pure or impure, consisting of either the same or different elements bonded together.
3. A polluted river contains elements in an impure form.
4. An unpolluted river contains molecules consisting of identical atoms bonded together.