

## Changes in Student Knowledge Structures in Science

Helena Dedic, Miriam Cooper and Steven Rosenfield

Vanier College

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ministère de l'Éducation dans le cadre du  
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(PAREA)

Le contenu du présent rapport n'engage que la responsabilité  
de l'établissement et des auteures et auteurs.

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## Abstract

The focus of this research program was to study and develop classroom teaching strategies that promote integrating knowledge and to develop an instrument that measures conceptual change. Our work was conducted in the domain of physics, particularly in Mechanics courses, and is founded on the theoretical perspectives of learning and knowledge structures posited by conceptual change theorists. The objectives of our research can be outlined as follows: to design a classroom intervention promoting conceptual change; to develop an instrument to measure conceptual change within the classroom context; to examine factors that confound the measurement of conceptual change, in particular when using the Force Concept Inventory (FCI); and to study how students think (differently) about qualitative versus quantitative physics problems. The methodology of our research varied with the objectives and was a blend of qualitative (semi-structured interviews) and quantitative (quasi-experimental research designs). Both the classroom intervention and the measure of conceptual change called the Motion questionnaire are still in the process of testing and development. The results of our experiment confirmed our hypothesis that students' unfamiliarity with test item format confounds the quantitative measurement of conceptual understanding when using the FCI. A single training session (teaching only strategies) significantly improved the performance of students on the FCI. It is noteworthy that the impact of the training session on the performance of low-scoring students was larger than that on high-scoring students. The results of this study are of particular importance to instructors in traditional lecture based classes who wish to use the FCI to assess their students understanding of Newtonian physics. In our study of student thought processes when solving qualitative and quantitative problems, we found that students tended to revert to their naive mental model of physics when faced with a qualitative problem. We also found that students perceive both problem types as complex. While experts eliminated such issues as air resistance and the choice of frame of reference from conscious consideration, students consistently stumbled on these issues. In addition, we found that students expressed their thoughts less coherently when they talked about the Newtonian model as compared to their discourse when using their own naive model. We attribute this effect to a fragmented knowledge structure.

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## 1. PROBLEM DEFINITION

As our society becomes increasingly technologically complex, the science education of our youth becomes ever-more critical. In Quebec, as well as around the world, the current science curriculum is undergoing close scrutiny because of an accumulation of evidence of ineffectiveness. It has been found that students who study science fail to integrate the fragmented knowledge acquired in different courses, and, as a consequence many students in Quebec have serious difficulty completing a DEC in the science program and end up transferring to other fields of study. Further, many of those who do manage to complete the program cannot use their disjointed knowledge in subsequent endeavours outside school. Evidently, the science program would benefit from classroom teaching strategies designed to focus on helping students integrate different aspects of science knowledge into a coherent and utile understanding.

### Deficiencies are perceived in many areas

**General scientific literacy.** Culliton (1989) reported that only about 6% of US and British citizens are scientifically literate, *i.e.*, know what scientists do, know something about the impact of science on society, or understand basic science terminology and concepts. Brooks (1989) showed that a lack of basic science literacy in symbol-manipulation will produce a workforce which is not prepared to face future job markets.

**Lack of success in science education.** The failure of science education is apparent from student records of low achievement and the poor retention rate of the science program. Lewin (1989) found that half or more of students enrolled in the science program failed to demonstrate much useful achievement after three or four years of study. Surveys done across North America, including here in Quebec, have demonstrated that the performance of our students is markedly below that of Japanese students. A report produced by the Conseil des Collèges (1988) finds the failure and dropout rates in CÉGEPs alarming. Similarly, Grant (1990) reported that 40% of first year Ontario science students failed their biology and mathematics courses. At Vanier College the number of science students who fail to pass at least four courses a term is increasing (Vanier College Science Review Board Statistics, 1996), and a study by Davis and Steiger (1996) found that as they graduate from CÉGEP, science students report a decrease of interest in the field. After interviewing a large sample of students, they attributed this finding to the instructional characteristics prevalent in college-level science courses.

**Low recruitment.** Tobias (1990) reported that many students with the potential to be excellent scientists opt for a non-scientific course of study and career because of the instructional strategy and classroom climate they experience in science classes.

**Consequences of ineffective science education.** An annual report of the Conseil des Collèges (1988, pp. 43 - 49) examined the consequences of failure and dropout in CÉGEP science programs, and found among them a negative impact on the individual student and his/her well being; a decrease in the credibility of the schooling system and the motivation of its staff; and, a high cost to our society. Evidence that science scores correlate positively with the economic growth of a country (Walberg, 1991), amply highlights the need to produce a scientifically literate community. However, as a result of poor recruitment and low retention in science programs, as well as of increased demand for highly science literate employees, a shortage of scientists is predicted for the near future (Tobias, 1990). Such a shortage will have a negative effect on both the pace of development of new technology and consequently on the competitiveness of our society in the world economy.

Even more alarming is the report prepared for Human Resources Development Canada (Lavoie and Finnie, 1997) which shows that science graduates rate the lowest in the job market as measured in terms of unemployment rates, salaries and job satisfaction. In their conclusions, the authors of this report state that among others the following question should be addressed: "Should graduates be better prepared for, or given more opportunity to engage in, creative or exploratory activities as opposed to more work-a-day problem solving activities?"

### The problem is fragmentation of knowledge

All science students in CÉGEPs are required to take nine compulsory science courses. It is assumed that in each of these courses students acquire both general and domain-specific science knowledge and problem-solving strategies. Subsequently, when they commence studies at a university, they are expected to use such knowledge to interpret, evaluate, and incorporate new information, and thereby build new domain-specific knowledge (Anderson, 1987; Bereiter, 1989). Unfortunately, students come to university with their knowledge fragmented between science disciplines, and even within them (Bagno, Eylon, & Daniel, 1993), which does not provide a solid base to build on.

**The consequences of knowledge fragmentation.** The knowledge acquired in a classroom is often taught in isolation from previous learning and experience. The result of such fragmentation is that many students graduate with a science DEC and yet are unable to transfer their knowledge to new domains, to solve problems which require insight from several domains, or even to use their knowledge in a new situation within a single domain. For example, graduates of a mechanics course are often able to recall verbatim the statement of Newton's Second Law which relates force to

acceleration. Often, they can even apply it to standard textbook problems, that is, to problems which they can superficially identify with sample problems taught in class. However, they fail to apply the very same law while solving nonstandard problems (Kalman, 1993; Halloun & Hestenes, 1985a). An example of this problem was remarked upon by the Nobel laureate Richard Feynman (Feynman, 1985). He describes students who, having understood all the internal relationships of some complicated physics concept, still failed to make connections between it and their general understanding of the world. For example the key-word-related phrase "What is Brewster's Angle?" solicited from students the retrieval of appropriate equations and calculations, but the real-world phrase "Look at the water" (where reflected light is being polarized through Brewster's Angle) solicited no links to the physics concept.

**Fragmentation of knowledge** is a particularly acute predicament in the domain of physics. Students develop their understanding of physical phenomena, such as motion, from real-world observations and experiences which start in infancy. They are very confident about using their model of the physical world because they have tested it repeatedly. Unfortunately, as long as the physics material taught in schools remains isolated from their prior understanding, students are likely to continue to fall back on these naive conceptions formed from physical experience when faced with physics problems where such models are really not applicable.

### Knowledge structure in the literature

The notion that the knowledge structure of students is fragmented is well-known, both amongst teachers who face this reality in the classroom every day, and also amongst researchers, who have developed a framework within which to discuss such problems. According to Ausubel (1963), "knowing something about an object" means that an individual has both concepts concerning the object, and relationships between such concepts in their knowledge structure. A knowledge structure (Ausubel, 1963; De Jong and Fergusson-Hessler, 1993) contains three types of concepts: concepts concerning objects and relationships between such concepts (declarative knowledge); concepts concerning principles or rules about using the concepts (procedural knowledge); and concepts concerning procedures for including new concepts into a knowledge structure (strategic knowledge). There are two important issues to be addressed concerning knowledge structures: how researchers conceptualize knowledge structures; and, how they believe knowledge structures change.

Investigators (Novak, 1988) believe that a knowledge structure is a web of inter-connected cells or nodes, each containing a concept. If two concepts are related in some way, then their cells are connected. Furthermore, the organization of a knowledge structure is hierarchical; that is, there are superordinate and subordinate concepts. For example, three domains of our knowledge, such as physics, biology, and mathematics can be thought of as parallel branches in the hierarchical tree that is a knowledge structure. The branches representing physics, biology and mathematics



should be inter-connected in many ways because many concepts in these domains are related to each other. A sub-domain of physics such as mechanics or optics can be represented by an offshoot branch in the hierarchical tree branch representing physics.

### Mental Models

An individual's concept of a particular object can be imagined as a sub-branch in the knowledge structure. Gentner and Stevens (1983) coined the term "mental model" to describe such a sub-branch within a knowledge structure, including its connections to the rest of the branches. A mental model is a cognitive representation of a specific concept which includes the definition of the concept, descriptions of various verbal attributes of the concept, its relationship to other concepts, procedural subroutines involving the concept, as well as non-verbal characteristics such as sounds, smells, and spatial attributes. For example, a mental model of an apple could be imagined as a part of the branch of a knowledge structure concerning biology. In addition, the mental model of an apple contains connections to other parts of the knowledge structure, such as: food (because the apple is edible); health care (because apples are healthy to eat); physics (because apples have weight and because one apocryphally landed on Newton's head); and many others. We shall use the term "knowledge structure" to describe an individual's overall organization of knowledge and we shall use the term "mental model" to describe a mental representation of a specific object or a concept, e.g., the mental model of a vector, and its connections within the knowledge structure.

### Conceptual Change

In attempting to describe how knowledge structures change, many theorists (Posner, Strike, Hewson, and Gertzog, 1982) borrow from Piaget (1954) and posit the dual processes of assimilation and accommodation. For example, one creates a mental model as one learns about an object. Thus, when we learn about an exotic fruit, such as soursop, we store in our memory its name, its properties (e.g., edible, sour, healthy, etc.), as well as knowledge of how to use this concept. In the process of creating the mental model of soursop we are actually connecting it to other mental models. This process is called assimilation. As a result of assimilation, a knowledge structure gains concepts and there are minor changes in structure. Assimilation may be accompanied by or followed by a radical restructuring of the knowledge structure called accommodation. Accommodation is a process in which the current organizing scheme of the knowledge structure is re-examined and replaced by a new scheme. When referring to accommodation some theorists use the terms "meaningful learning", "deep processing", or "conceptual change". We will use the last of these terms.

### Rote Learning = No Conceptual Change

Ausubel (1963) introduced the concept of rote learning or surface processing to

distinguish it from what he called meaningful learning. In rote learning, information about an object is stored without translating it to the learner's own vocabulary, without relating it to the learner's existing knowledge structure, and without deciding under which existing domain the new concept should be stored or to which branches in the knowledge structure's hierarchical tree the new concept should be connected. That is, neither assimilation nor accommodation with an existing knowledge structure is sought. Consequently, the existing knowledge structure is not replaced by a new one in this process of learning. In other words, the rote learner fails to make a conceptual change. The knowledge structure resulting from such learning is ill-structured (Resnick and Ford, 1981) because it contains concepts with only a few links between them, and thus does not resemble the highly inter-connected knowledge structure of experts.

### Conditions for Conceptual Change

Researchers (Ausubel, 1963; Novak, 1988; Roth, 1990; Posner, Strike, Hewson, and Gertzog, 1982; Pintrich, Marx, and Boyle, 1993; Lee & Anderson, 1993) contend that students often do not assimilate and accommodate new ideas in the classroom. They have suggested that conceptual change occurs only if certain cognitive and motivational conditions are satisfied. These conditions are related to: the task (e.g., learning a new concept can only be meaningful if the concept is understandable to the learner); the classroom setting (e.g., mistakes are seen as positive or students have enough time to think about the new concepts ); and, the learners' characteristics (e.g., learners' goals, self-efficacy).

For conceptual change to take place the learning task must be potentially meaningful. Learning tasks must be designed so that they require meaningful learning and fall within the students' learning capacity. For example, learning a random list of words cannot be meaningful because there is no inherent logic to the list. Similarly, learning Shakespeare's sonnets is not potentially meaningful to a typical ten year old. In addition, a motivational pre-condition for conceptual change is that a task should be perceived by students as authentic and challenging. Meaningful learning is likely to occur if students are solving a problem whose solution they are genuinely curious about. For example, students enthusiastically graph their food intake and count calories because they are genuinely interested in the resulting graph and the conclusions they can draw from it.

In order for conceptual change to take place the classroom setting must provide appropriate conditions; for example, sufficient time must be allocated for task completion and the teacher should model thought processes. Donald (1994) found that students in physics classes opted for rote learning because they were overwhelmed by the amount of work and lack of study time. Additionally, the classroom setting can promote meaningful learning by: employing appropriate authority structures; using evaluation methods which are improvement-based; recognizing mistakes as an integral part of the learning process, etc. Romano (1993) reports a mismatch between

students' and their science teachers' perception of "learning for understanding" in their science courses. Students rated science courses significantly less effective in promoting the development of thought than courses in other disciplines, while science teachers rated themselves significantly higher than teachers in other disciplines as using approaches which promote the development of thought.

For conceptual change to take place the learner must also possess an appropriate prior knowledge structure. Students' knowledge structures often contain mental models which may be well formulated, albeit incomplete. Alternatively, they may possess ill-structured prior mental models, which are called misconceptions (e.g., Hewson, 1984; Clement, 1982; Lijnse, Klaassen, & Eijkelhof, 1993; Rastovac & Slavsky, 1986; di Sessa, 1982; di Sessa, 1983; McCloskey, 1983; Mc Dermott, 1984; Styer, 1996). Such ill-structured mental models have few relationships to other concepts within a knowledge structure, some relationships may be wrong or the entire organization of concepts may not resemble experts' knowledge structures. Dicke and Farrell (1992) and Donald (1994) report that there is a mismatch between students' prior knowledge structures and teachers' expectations of their prior knowledge, and, consequently, without a base to build on, students don't achieve meaningful learning of new material.

Another aspect of a student's knowledge structure that can influence new learning is the strategic knowledge of the prior mental model. According to Pintrich and his colleagues (Pintrich, Marx, and Boyle, 1993) a prior knowledge structure influences perception and selective attention to new information. Students may mis-perceive or choose to ignore data that contradicts their prior concepts. In such cases, the students' prior mental model is a hindrance to learning. In addition to the cognitive readiness required of the learner, there are motivational pre-conditions for conceptual change. The learner must have an appropriate attitude toward the content and the motivation to learn it. That is, learners must value their learning and they must have (intrinsic or extrinsic) goals directed towards learning. It cannot be expected that learners who do not value knowledge of physics or who do not have the goal of learning physics will spend time and effort to create a mental model of force which resembles that of experts. Researchers (Pintrich, Marx, and Boyle, 1993; Pajares & Miller, 1994; Strike & Posner, 1992) show that self-efficacy, along with mastery goals and deep processing strategies, correlate positively with meaningful learning. Pajares and Miller (1994) show that students who score low on self-efficacy scales also exhibit diminished effort compared to their high-scoring counterparts.

Finally, as an additional pre-condition for conceptual change, the learner must have appropriate epistemological beliefs concerning information and learning. Schommer and her colleagues (Schommer, Crouse & Rhodes, 1992) label students who believe that "to learn is to remember a set of simple facts" as students who believe that knowledge is simple. They have demonstrated that simple knowledge beliefs are negatively correlated with comprehension and meta-comprehension. However, they have also found that these deleterious effects of the belief in simple knowledge can be

mediated by appropriate classroom instructional strategies.

### Our Research

The original objectives of our research program were to: 1) design a classroom intervention for a physics course in Mechanics that set appropriate task and classroom conditions so as to promote conceptual change from students' common-sense understanding of the physical world to a Newtonian-based mental model; and 2) to measure whether students successfully achieved conceptual change. Conceptual change is currently assessed qualitatively through interviews and questioning, with only one standardized instrument available (the Force Concept Inventory) with which to measure only concepts related to force in Mechanics. Since we wanted to be able to perform a quantitative study, we attempted to create and standardize a measurement tool to assess students' understanding of the concept of inertia and the relationship between force and change of velocity. We set up our intervention, ran a pilot study on our "Motion Questionnaire" and came to realize what external factors were influencing our attempt to measure conceptual change in a quantitative manner. This altered our course of research as we began to question whether any standardized instrument can be validly used to measure conceptual change. Both the Motion Questionnaire and the FCI assess students conceptual understanding on the basis of their solution of qualitative questions. However, interviews with students revealed that they think differently about qualitative problems as compared to their thinking about quantitative problems. We felt that we needed to know more about these differences before continuing with further development of the Motion Questionnaire and experimenting with instructions that promote conceptual change. In the subsequent chapters we will outline the course of this research to date: the intervention that we developed; the Motion Questionnaire and the results of the attempt at validation; a study of the existing standardized instrument; and, a study which contrasted student approach to qualitative and quantitative problems.

## **2. DESIGN OF AN INTERVENTION**

Conceptual change theorists have developed an instructional design to be used when students' prior mental models include misconceptions (Posner, Strike, Hewson, and Gertzog, 1982; Posner & Strike, 1992; Chinn and Brewer, 1993; Chinn and Brewer, in press; Pintrich, Marx, and Boyle, 1993). The goal of these interventions is to replace a prior mental model by a new mental model. These theorists' classroom interventions share two common characteristics: they create student dissatisfaction with their current mental models, and then focus on students' formulation of a model. These goals are achieved by first introducing materials which promote students' dissatisfaction with their current mental model. A simple presentation of dissonant data does not usually generate dissatisfaction because the current mental model may be well entrenched within a knowledge structure, and, as a result, students may misperceive dissonant data. To overcome this obstacle dissonant data should come from multiple credible sources and should be unambiguous. Second, classroom interventions focus students' perception on new mental models. Such new models must be intelligible or understandable by students and should be related to students' existing knowledge structures so that students perceive them as plausible. Further, such new models should be seen as fruitful; that is, students must perceive that the new models are easy to use in solving problems, generating correct answers, correctly predicting outcomes of experiments, etc.

Our intervention strategy differs from those above in that our intervention aims to relate a current mental model to a new mental model rather than to simply replace the current one. We adopted this approach since it has been found (Tiberghien, 1989; Linn & Songer, 1991) that attempts to eradicate prior mental models result in ill-structured new knowledge. In our opinion, experts maintain their current mental model when accommodating a new model by adjusting their sense of when the current model is appropriately used. According to cognitive flexibility theorists (Spiro, Feltovich, Jacobson & Coulson, 1991), focussing on relating new information to prior understanding is necessary in order to ensure that students achieve a complex knowledge structure similar to that of experts. If students are taught in a way that either eradicates a prior mental model or isolates a prior model from a new one, their knowledge structure will be fragmented, resulting in an inability to choose between and use the appropriate model in a novel situations. Thus, our intervention seeks to discuss both the Newtonian model of the physical world as well as students' current mental model, as developed from physical experience, and to compare and contrast their relative usefulness in problem-solving in physics.

After reviewing the different instructional designs described in the literature, we decided that our instructional intervention in both the experimental and control classes would be based on an interactive-engagement rather than a traditional lecture format, since Hake's (1998) study showed that students in interactive physics classes outperform students in traditional classes.

## Methodology

**Participants.** In this study, participants were 36 Vanier science students taking Mechanics 203-101. Most participants were either repeating 203-101 or had taken Introduction to College Physics, 912-017, previously. There were 16 students in the experimental and 20 students in the control conditions.

**Intervention** Each of two researchers gave a 105 minute intervention to either the experimental or control class. In order to create cognitive dissonance, students in both groups were asked to solve a problem which requires a Newtonian physics model in order to be solved correctly, but which often compels students to use their pre-Newtonian or "commonsense" notions about the physical world. The students could arrive at one of two answers, depending on which model they used (Newtonian or commonsense). In the experimental class, the researchers and students discussed and debated misconceptions and emphasized the difference between the commonsense and Newtonian models. In the control class, however, the researchers didn't compare and contrast the models, but simply explained the correct solution and dismissed using the commonsense model as an error. To compensate for the time spent discussing the two models in the experimental class, the researcher teaching the control class solved additional problems. Both intervention classes lasted 105 min, and at the end of this period students in both classes obtained print-outs of class notes. These notes also included a sixteen-problem homework assignment which was to be submitted one week after the instruction (Notes for both the experimental and control class as well as the problem set are to be found in the Appendices I and II respectively.). As an incentive for students to do the problems, a grade for the homework assignment was included in the grading schema for the course. There was no quiz at the end of the instruction since students were interactively engaged in group tasks, and the researchers assessed the students' knowledge by reviewing the records of student discussions (Sample of student activities can be found in Appendix III.). It is important to emphasize that both the experimental and control instructions were similar in that the same problem-set was used, they both had the same interactive design, and both interventions were of the same 105 minute duration.

During the pilot test, students completed a questionnaire that enabled us to assess the impact of the intervention, the clarity of instruction and the timing of the instruction (Appendix IV). In addition, the content and the instructional design of interventions was evaluated by consultants on this project as well as by members of the physics department. We also asked five second year students and two first year students to read the print-outs of the class notes, to comment on the readability of the text, and to point out difficulties encountered in completing interactive tasks. These students did not solve the problems on the homework assignment but did comment on their understanding of the text and the relevance of the problems. All comments and observations during the instruction led us to improve the text of the class notes (Appendix I and II).

### 3. MOTION QUESTIONNAIRE

The second issue addressed in this study is the measure of conceptual change. Educational researchers use semi-structured interviews (Searle & Gunstone, 1990; Dykstra, Boyle, & Monarch, 1992; Halloun & Hestenes, 1985b; Cobern, 1989) or records of think-a-loud sessions (Larkin, 1992)) to assess students' conceptual change. Because of the qualitative nature and time demands incurred with both of these methods, they are impractical in the context of regular classroom practice. Standard achievement measures (examinations), have been shown to be an inadequate measurement tool of conceptual change because of the effect of instruction (McDermott, 1993). To overcome these obstacles, Hestenes, Wells and Swackhammer (1992) developed a questionnaire to assess whether students acquire a Newtonian model of the concept of force during the course of physics instruction. Using this inventory as a pre-test and a post-test, researchers as well as instructors can assess whether their instruction led students to change from a naive concept to a Newtonian concept of force. The problem that faces instructors seeking to assess their students' conceptual understanding of important physics concepts other than force is that the development of similar questionnaire involves extensive work and expertise. Consequently, teachers face a serious challenge if they wish to test whether their students achieved conceptual understanding of various physics concepts as result of what they were taught. In order to address this issue we attempted to develop a template for an assessment instrument, one that could be adapted to measure conceptual change in any domain of knowledge.

The construction strategy for the template is based on an approach proposed by Goldsmith, Johnson and Acton (1996). These researchers select a set of concepts relevant to a particular domain of knowledge and ask students to rank the proximity between pairs of those concepts on a scale of 0 to 7, where 0 = no relationship and 7 = a very close relationship. The rankings between concepts generated by students are entered into a so-called proximity matrix on a computer, and Pathfinder software converts the proximity matrix into a concept map. According to these authors, an analysis of the differences between the concept maps generated from expert matrices and those of students allows researchers to assess the similarity between students and experts knowledge structures. It has been shown that student-expert similarity of knowledge structure is a predictor of domain performance (Diekhoff, 1983; Fenker, 1975; Thro, 1978) and it was also shown that students knowledge structures become more similar to experts with instruction (Geelsin & Shavelson, 1975; Shavelson, 1972). Goldsmith et al. (1996) showed that students with similar Pathfinder concept maps also achieve similar class performance.

Although Goldsmith's approach has been successfully used in the social sciences we anticipated difficulties in using this approach in the domain of physics and mathematics. The difficulty stems from the meaning of the concept of proximity, which in Goldsmith's work is rather loose. In physics and mathematics, a relationship

between two concepts is usually precise: e.g., force is equal to mass times acceleration. In keeping with the traditional approach of physicists and mathematicians, we decided to define the concept of proximity precisely. Instead of selecting a set of concept words, we used a set of concept phrases relevant to the topic, e.g., "the car is accelerating", "the velocity of the car is increasing", "a force is exerted on the car", etc. We then asked students about the logical relationship between pairs of these concept phrases, providing them with four alternatives: 1. "a tells you that "b"; 2. "a is consistent with "b"; 3. "a is not consistent with "b"; and, 4. "a is unrelated to "b". For example, such pairs included:

- |   |
|---|
| 1 "a tells you that "b"<br>2 "a is consistent with "b"<br>3 "a is not consistent with "b"<br>4 "a is unrelated to "b" |
|---|

	statement "a"	⇓	statement "b"
1	the car is accelerating		the velocity of the car is increasing
2	the velocity of the car is increasing		the car is accelerating
3	a force is exerted on the car		the car is accelerating
4	the car is accelerating		a force is exerted on the car

These pairs of phrases show different relationships between the concepts of velocity, acceleration and force. In examining the first pair, we see that "the car is accelerating" **is consistent with** "the velocity of the car is increasing" (the velocity of the car may be decreasing) while for the second pair "the velocity of the car is increasing" **tells you that** "the car is accelerating".

We saw numerous advantages in using this approach in constructing the proximity matrix. First, in our discussions with members of the Varier Physics department (Drs. Hetherington, Gujrathi and Cowan) as well as with our consultant Dr. Kalman of Concordia University, instructors and researchers had little difficulty in constructing the concept phrases. Second, the proximity ranking by instructors and researchers was the same. Thus, we could expect that an expert concept map based on the proximity matrix generated would be highly similar to other experts' concept maps and would reflect an expert knowledge structure of relevant concepts. Third, scoring and evaluating student concept maps derived from their rankings would be done automatically by Pathfinder. This means that this relatively simple procedure could be conveniently used within a regular classroom context, which would encourage instructors to use it in addition to traditional exams to more accurately evaluate



students' conceptual understanding.

To create our measurement tool on students' conceptual understanding of the relationship between inertia, force and change of velocity, we selected twelve concept phrases on these topics. This Motion Questionnaire asks students to evaluate the proximity of these concepts by ranking the relationship between phrases representing each of these concepts, as illustrated above. (The complete Motion Questionnaire is found in Appendix VI).

The content validity of the questionnaire was evaluated by experts Dr. Kalman of Concordia University, Dr. Heatherington, Dr. Gujrathi and Dr. Cowan of Vanier College and these experts agreed on a unique 12 x 12 proximity matrix. In order to establish the reliability of our instrument we first pilot-tested it with five students. We looked at individual items to see whether students who answered differently than experts truly had an erroneous understanding of the concept or simply misunderstood the meaning of the item itself. Based on this pilot study we modified the instructions given to students as to how the questionnaire was to be filled out, and improved the clarity of the concept phrases. Since students had difficulty understanding the logical relationships between phrases and ranked them in an unpredictable manner, we also included a short training session on logical reasoning. The training session was administered directly prior to testing and made use of pairs of simple mathematical phrases, e.g., " $2X = 4$ " and " $X = 2$ ".

Subsequently we tested the instrument on a larger scale, running it in a class of approximately 30 students. We interviewed five of these students to establish whether the results of the Motion Questionnaire reliably predicted student conceptual understanding of concepts of inertia, force and change of velocity. Despite the logical reasoning training session, students continued to have difficulty with determining the relationship between phrases. A common error was that students justified their ranking of a pair of phrases "a" and "b" by arguing that since "a" is true whenever "b" is true, then "b" must be true whenever "a" is true. However, this logical reversal was not consistently performed even by the same student, so that misunderstanding of logical statements confounded our judgement concerning student understanding of physics concepts. As result of this confusion, student proximity ranking could not be used to reliably reflect conceptual understanding of physics.

We ran a second pilot test with 22 students enrolled in Mechanics 203-101. We developed a half-hour instruction module concerning logical reasoning. The discipline content was  $x$  versus  $t$  and  $v$  versus  $t$  graphs, a topic that is found in both mathematics and physics. Students' ranking of the proximity of related concepts agreed with their results on the post-instruction quiz. Their average score of 80% indicated their conceptual understanding. However, when these same students were confronted with the Motion Questionnaire they were again confused. We hypothesize that students who are lacking a strong background in logical reasoning are only able to reason

correctly if the content of the statements is sufficiently simple. The complexity of the concepts tested by the Motion Questionnaire may draw students to apply the principles of logic incorrectly.

We also observed that the format of the Motion Questionnaire statements was causing students to misinterpret them. The statements were very different from those encountered in typical physics problems. When the meaning of the statement was clarified by the interviewer, students' ranking reliably reflected their conceptual understanding of the concept of physics. Because of similarities between our instrument and the FCI, this finding led us to doubt whether the Force Concept Inventory could be considered a reliable measure of students' conceptual change. The format of items in this instrument is very different from standard physics problems and it is possible that students may misinterpret or misunderstand their task. We hypothesized that an instruction on what is expected of them might improve students' scores on the Force Concept Inventory. The next chapter describes the experiment in which we verified this hypothesis.

#### **4. FORCE CONCEPT INVENTORY: LESSON TO BE LEARNED**

In the midst of the debate in the physics community as to what the Force Concept Inventory (FCI)(Hestenes, Wells, Swackhammer, 1992) actually measures, we want to report on our investigation of the effect of a training intervention on FCI scores. In our own research on conceptual change (as defined by Posner, et al., 1982), we attempted to develop an instrument to measure conceptual understanding in physics. As noted above, while interviewing students during the validation process, we became aware that test-construction issues such as item format and the precise wording of qualitative questions affected student interpretation of what was expected of them, and how they should answer. It was clear that these issues were interfering with our ability to measure their conceptual understanding with validity. Reflecting on our instrument's similarities to the FCI, we wondered whether these same issues might be confounding variables in students' scores on that test. In other words, we questioned whether the reported poor performance by students on the FCI (Hestenes et al., 1992, Hake, 1994) is solely due to students' incorrect conceptual understanding, or whether it is, at least in part, a reflection of the fact that the format of test items on this instrument is very different from that of standard physics class problems. If the latter were the case, we hypothesized that students' FCI performance would improve as a result of a short training session teaching them to recognize the novel question format as physics, and to apply their physics knowledge to solve such questions. This section of our report is on the results of an experiment testing this hypothesis.

##### Background

Hestenes et al. (1992) developed the FCI to assess student understanding of the many facets of the Newtonian concept of force. The FCI is a multiple-choice test which gives students a choice between one solution derived from a correct understanding of Newtonian mechanics and four other solutions based on "commonsense" alternatives. In this paper we will use the term "FCI-like" to refer to problems like those on the FCI while we use the term "physics-like" to refer to quantitative problems typically found in traditional physics texts and exams.

Although a problem on the FCI is of a qualitative nature and looks simple to a professional physicist, when the FCI was used to test students ranging from high school to university level across the US and Canada, it was found that students are less successful in choosing the correct qualitative answer than they would be in calculating the correct answer for a physics-like problem (Mazur, 1997). These results were considered to indicate that students, despite being successful in solving problems faced in traditional courses, retain their naive conceptions about the physical world and thus fail to correctly solve FCI-like problems. Because the FCI was accepted as a diagnostic tool of student understanding of the concept of force, the results caused dismay in the physics-teaching community, and promoted the use of interactive engagement (IE) methods in physics instruction intended to improve conceptual

understanding.

Recently, concerns have been raised as to what the FCI actually measures (Huffman & Heller, 1995; Steinberg & Sabella, 1997), and what lessons one should draw from the findings (Griffith, 1997). The results of testing students using the FCI may be influenced by a number of factors such as its multiple choice format, the qualitative nature and wording of the problems, and whether the method of instruction is traditional or interactive engagement in nature.

### Multiple choice format of the FCI

Steinberg and Sabella (1997) suggested that performance on the FCI may be influenced by its multiple-choice nature which may trigger responses students would not themselves generate.

Another issue came to light in our research. Students often solve multiple choice questions using an elimination strategy, where choices are only marginally influenced by any conceptual understanding. To illustrate the kind of thinking process involved, below we provide a transcript from an interview with an 'A' student who had recently graduated from Calculus-based Mechanics. The student was describing the way he answered FCI item #23 (see Appendix 1):

Student "I'll be honest with you guys. If this was a test situation I know that these two are wrong, because I know that there's only one choice of this (points to d), one choice of this (points to e) and three choices of this a, b and c. Then it's more likely that these are the ones that are going to be right. Maybe you can't really follow."

Researcher: "I follow".

Student: "I suppose if somebody knows the answer to this quite well, he'll have no trouble knowing these are completely wrong, so he'll have no trouble erasing these (points to d and e) and he'll be narrowed down to these three answers (points to a, b, c). And he'll have no trouble with these three answers. What makes it even easier, is that it's kind of given away by this (points to path e). Once they've figured this kind of trick out, they would say 'of course, it goes in this kind of hyperbolic path'. If you were to give me this, this straight line, I would say this can't possibly be right. But since you have a hyperbolic kind of movement for this one (points to e), I would have chosen this one (points to c), so I know that this kind of path is right."

Although the student uses logical reasoning based on experience with multiple choice tests to choose the correct path, it is difficult to judge whether he has an understanding of the physics concept involved.

### Qualitative nature of the FCI

Mazur (1997) raised the issue of the differences between qualitative and quantitative questions. He showed that if quantitative and qualitative problems on the same concept were paired, many students in a traditional lecture class demonstrated a serious conceptual misunderstanding in their solution to the qualitative version of the

problem despite being able to produce the correct numerical solution in the quantitative version. He attributed this difference in their performance to students' using "recipes" or "algorithmic strategies" in solving physics-like problems without developing an underlying conceptual understanding.

Steinberg and Sabella (1997) studied students' performance on qualitative open-ended exam questions. They found that certain students performed better on these problems than they did on the FCI, even though they were matched for conceptual content and difficulty. They speculated that the wording of the FCI-like problems invoked thoughts of real world experiences, while the wording of their open-ended exam problems invoked thoughts of physics-like problems.

In another study<sup>1</sup> we interviewed students on their thinking when solving FCI-like problems versus physics-like problems. When students were given a qualitative and a quantitative version of the same problem, even if they had not received instruction in relevant concepts, they all readily answered the qualitative version while refusing to attempt to solve the quantitative version. When they had received instruction in relevant concepts, they tended to use different strategies, deducing the solution from their own experience to answer qualitative problems but using physics procedures to solve quantitative problems. For example, we gave a class of students two versions of a problem where a can is dropped from a moving car, one qualitative and one quantitative. For half the class, the qualitative version preceded the quantitative one while the order was reversed for the other half. Fragments from the transcript of a typical interview exemplify the different approach used by a student when answering, back-to-back, the same conceptual problem worded first qualitatively and then quantitatively.

*FCI-like problem: A driver of a car travelling North at a steady 30m/s drops an empty Coke can. The diagrams below show the car at the moment the can is released. The dashed lines represent possible paths of the Coke can. Discuss the path in each diagram in terms of how likely you think the Coke can is to follow that particular path.<sup>2</sup> Explain your reasoning in each case.*

Student: "... If he dropped it in the car, then it would just drop to the bottom. There would be this one (points to d) ... But if he held his hand out the window and dropped it, then the car would continue to move forward and it would drop to the ground behind him and he would have passed it already (chooses e)." ...

Interviewer: "... you are eliminating these three (paths). Why?"

Student: "... you couldn't drop a can out the window and have it end up further "ahead" of you than the car is, and in all three of these, although they are different shapes, the can

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<sup>1</sup>The results obtained in that study will be published shortly.

<sup>2</sup> Note that suggested paths a ... e correspond to the paths in FCI item 23. Neither problem shows the path of the moving vehicle after the drop.

ends up in front of the person.

*Physics-like problem: A passenger dropped an empty beer bottle from a train travelling at 40m/s headed due south. The bottle was dropped from a point 2 m above the ground. Determine the horizontal distance the beer bottle travelled before landing.*

Student: "What's gonna happen to the bottle is that it starts out here and it's gonna end up going like that (*draws diagram depicting path similar to c in the previous qualitative question*), down to the ground. And this is gonna be 2 m, and we are looking for this horizontal distance. ... It started with a horizontal velocity of 40 m/s ..." (*The student then goes on to solve the problem. In his discourse he displayed a firm grasp of the concept of inertia.*)

Note the different thought process indicated by the student's responses to the two questions. He responds to the FCI-like problem by recalling his own experience of being in a car, which influences his interpretation of the picture since he argues against the can going "ahead" of the car. However, for the physics-like problem he sketches without hesitation a trajectory that is identical to path *c* of the FCI-like problem, and then proceeds to draw on his knowledge of physics to formulate the correct answer. The student demonstrated no awareness of the blatant contradiction between his responses, and expressed puzzlement when the inconsistency in his thinking was pointed out by the interviewer. It appears that cues such as "determine" and "the horizontal distance" elicited a link to problem-solving strategies in his approach to the physics-like problem. Instruction that teaches students to attend to physics cues, rather than to personal experiences, might have helped this student.

### Interactive engagement methods

Hake (1998, p.65) identified "IE methods as those designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors". Traditional courses are those that "make little or no use of IE methods, relying primarily on passive-student lectures, recipe labs and algorithmic-problem exams". Hake's survey of 1998 indicated that performance gains on the FCI were higher for students enrolled in courses which made substantial use of IE methods. Numerous studies of IE methods (peer instruction, tutorial workshops, workshop physics) have shown them to be effective in improving the performance of students on qualitative questions and the FCI.

The above results imply that IE instruction is better than traditional instruction at promoting conceptual understanding of Newtonian concepts (as measured by the FCI). We wondered if an alternative explanation might be that the better performance on the FCI by students in IE courses was due, at least in part, to their exposure to qualitative questions within that instructional setting. Students enrolled in traditional lecture courses may have less experience in answering qualitative problems than students in IE courses. Although most physics text books include qualitative problems, called

"Questions", that precede the standard numerical problems, many teachers do not assign such questions or use them on tests (Dicke, 1995). It is likely that FCI-like problems are discussed in class and posed on exams in IE courses. Browsing through IE textbooks (McDermott, Knight, Mazur), we found support for this conjecture.

We wanted to clarify to what extent the aforementioned issues might play a role in the FCI scores and decided to test whether training students to use appropriate problem-solving strategies when answering FCI-like questions would improve their score on the FCI. The training would not be designed to teach concepts, but rather to demonstrate to students that they should use the same strategies to answer FCI-like questions as they do to answer physics-like problems.

### The Experiment

**Participants** We compared the FCI performance gains of two groups of students taught in college-level introductory physics by the same instructor. Both classes followed the same curriculum and used the traditional lecture format in class. The students had comparable academic profiles with high school science averages between 65% and 70%, which is why they were required to enroll in a remedial program which includes a pre-calculus course, an introductory chemistry course, an introductory physics course (Introduction to College Physics) and a learning-to-learn course (Introduction to College Science). The experimental class of 34 students ran in the fall term of 1997, while the control class of 22 students ran in the fall term of 1998.

**Design** In this quasi-experimental study we used a 2X2 mixed factorial design with one between-group factor with two levels (experimental, control) and one within-group factor (pre-test, post-test).

**Pre-test/Post-test:** The researchers administered the FCI as a pre-test (Pre) during a regular lab period two weeks before the end of the course in both groups. All students were given the FCI as a post-test (Post) immediately following their final exam.

During an interview the physics instructor revealed that he did not teach all the material pertinent to all FCI items. Therefore, we divided the 29-item FCI into two subsets: Set A includes all questions (19 items) relevant to material taught in the course, while Set B includes all other questions (10 items). In the results below we examine student performance on the entire FCI questionnaire, as well as on the two subsets.

**Training** A 75-minute training session on answering FCI-like questions was given to the experimental class one week after the pre-test. The session was given by a member of our research team and used IE methods. It should be noted that the researcher had used IE methods all semester with the same students as their teacher of Introduction to College Science. Even though the session was only 75 minutes long,

the trust that existed between the instructor and the students made them receptive to her intervention. Instead of a training session, the control class received a regular 75 minute tutorial in preparation for the final exam from their physics instructor.

The instructional materials consisted of a set of nineteen problems. We generated the problem set (Appendix VII) by translating physics-like problems from the course text into FCI-like problems. All problems were presented in the same format as those on the FCI, but were different from FCI items in order to avoid "teaching to the test". We examined student performance on each item to assess whether the effect of training was due more to the content of the practice problems than due to strategies used. The nineteen practice problems were chosen before we were aware which FCI material was covered in the course and which was not.

During the session the researcher used IE methods and started by modelling the solution of one problem. The researcher emphasized that FCI-like problems are solved by first drawing a diagram of the situation and then thinking of the physics involved, not by choosing an answer that made sense from their own perceptions or by using elimination strategies. The researcher pointed out that the problems described real-world situations using colloquial language which may jog memories of real-world experiences. The class discussion contrasted the unreliability of individual perceptions to the predictive power of Newtonian principles. In conclusion, the researcher told the students to wear their physicists' hats and use the same strategies for solving FCI-like problems as physics-like problems in order to be successful on the FCI. The second problem was done in discussion with the entire class. The third problem was done by small groups reporting to the whole class. After the instruction students were encouraged to finish the remaining eighteen problems at home, and told that they could pick up solutions or seek help if needed from the researchers. A number of students picked up the solutions, but only a few sought additional help. A sample problem follows:

In the spin cycle of a washing machine, the drum rotates and water flies out of the hole of the drum. Here are common explanations of the physics involved. Which is correct?

- a. Centrifugal force causes the clothes to move to the walls of the drum.
- b. A force acts away from the centre so that the water is pushed straight out the holes of the drum.
- c. The spinning action forces the water out of the holes leaving the clothes dry.
- d. The drum exerts a normal force on the clothes to keep them inside.
- e. The centrifugal force balances the centripetal force.

*Practice Problem*

**Student incentive** Steinberg and Sabella (1997) felt that the difference they observed in student performance between the FCI and final exam might be due in part to the fact



that the FCI did not count towards students' grades. Consequently, as an incentive to do their best on both tests, students in our study were told that they could earn up to 5 bonus points towards their final grades as a function of their FCI scores.

## Results

**Equivalence of experimental and control classes** The experimental and control groups can be considered equivalent if it can be shown that there was no difference between the two groups' performance on the FCI pre-test. Table 1 shows the average pre-test score  $\langle \text{Pre}_t \rangle$  and the standard error of the mean (*sem*) for the experimental and control groups. The mean FCI pre-test score was 41.68% (*sem* 2.49) for the experimental class, and 41.69% (*sem* 3.19) for the control class. A two-tailed t-test for independent samples yielded a probability,  $P_t$ , of 0.998 that there is no significant difference between these two means.

Table 1  
Comparison of the Pre-test Scores for experimental and control classes

Measure	Experimental	Control	$P_t$
$\langle \text{Pre}_t \rangle$ ( <i>sem</i> )	41.68% (2.49)	41.69% (3.19)	0.998

**Improvement in FCI score.** We examined the change between the mean pre-test score  $\langle \text{Pre}_t \rangle$  and the mean post-test score  $\langle \text{Post}_t \rangle$  for both the experimental and control conditions. We found that there was significant improvement in both classes between the pre-test and the post-test score. The mean FCI score rose from 41.68% to 52.64% for the experimental class, and from 41.69% to 46.40% for the control class. The one-tailed t-test for repeated measures showed that the change was significant for both classes ( $t(33) = 5.63$ ,  $p < 0.001$ ,  $t(21) = 3.70$ ,  $p < 0.001$ ). Similarly, the mean FCI score increased significantly.

In order to see whether students performed differently on subsets of items covered (Set A) and not covered (Set B) in the course, we examined the change between the mean pre-test score and the mean post-test score for the two subsets. The mean score for Set A rose significantly from 42.26% to 57.12% for the experimental class ( $t(33) = 4.96$ ,  $p < 0.001$ ), while the mean Set A score increased from 45.7% to 49.28% for the control class ( $t(21) = 1.65$ ,  $p < 0.1$ ). We noted that the improvement in scores on Set B was not statistically significant ( $t(33) = 1.16$ ,  $p < 0.1$ ) for the experimental class. On the other hand, the improvement in scores on Set B (the mean pretest score is 34.09 and the mean post-test score is 40.91) is significant ( $t(21) = 2.05$ ,  $p < 0.05$ ) for the control class. Table 2 shows these results.

Table 2  
Comparison of mean FCI scores for Experimental and Control Classes

	Exp. FCI	Control FCI	Exp. Set A	Control Set A	Exp. Set B	Control Set B
<Pre <sub>i</sub> > (sem)	41.68% (2.49)	41.69% (3.19)	42.26% (2.82)	45.7% (3.79)	40.59% (2.85)	34.09% (3.56)
<Post <sub>i</sub> > (sem)	52.64% (2.5)	46.40% (3.7)	57.12% (2.57)	49.28% (4.43)	44.12% (2.57)	40.91% (4.21)

**Effect of training on FCI score** The difference between the mean gains  $\langle G_i \rangle = \langle \text{Post}_i - \text{Pre}_i \rangle$  for the experimental class and the control class is a measure of the effect of training. However, gains may also be affected by the ceiling effect and, consequently, may decrease as pre-test scores increase. To account for this possibility and control for it statistically we also computed the normalized gain per student as the ratio of the actual gain  $G_i = \text{Post}_i - \text{Pre}_i$  to the maximum possible gain  $G_{i,\text{max}} = 100 - \text{Pre}_i$ . The mean normalized gain,  $\langle g_i \rangle$ , is

$$\langle g_i \rangle = \langle G_i / G_{i,\text{max}} \rangle = \langle (\text{Post}_i - \text{Pre}_i) / (100 - \text{Pre}_i) \rangle.$$

The coefficient of correlation  $r$  was also calculated to measure the correlation between gains  $G_i$  and pre-test scores  $\text{Pre}_i$ . This assesses how gains vary with pre-test scores and whether the relationship between the gains and the pre-test scores changed as a result of the training.

**Gains:** Table 3 shows the mean gains and the normalized mean gains on the whole FCI, as well as on the subset of items pertaining to material covered in class (Set A) and on items not covered in class (Set B) in both the training and control conditions. We found that the mean gain  $\langle G_i \rangle$  (10.95%) in the experimental class is significantly higher than the mean gain (4.70%) in the control class (one-tailed t-test for independent samples:  $t(54) = 2.38$ ,  $p < 0.05$ ). When we examined the difference between the mean gain (14.86%) for the experimental class and the mean gain (3.58%) for the control class, we again found that the gains were significantly higher in the experimental ( $t(54) = 2.73$ ,  $p < 0.01$ ) for Set A while the difference was not significant ( $t(54) = 0.71$ ,  $p < 0.1$ ) for Set B (the mean gain is 3.53% in the experimental and 6.82% for the control class).

**Normalized gains:** The examination of the normalized gains yielded similar results. We found that the mean normalized gain  $\langle g_i \rangle$  (0.19) in the experimental class is significantly higher than the mean normalized gain  $\langle g_i \rangle$  (0.1) in the control class (a

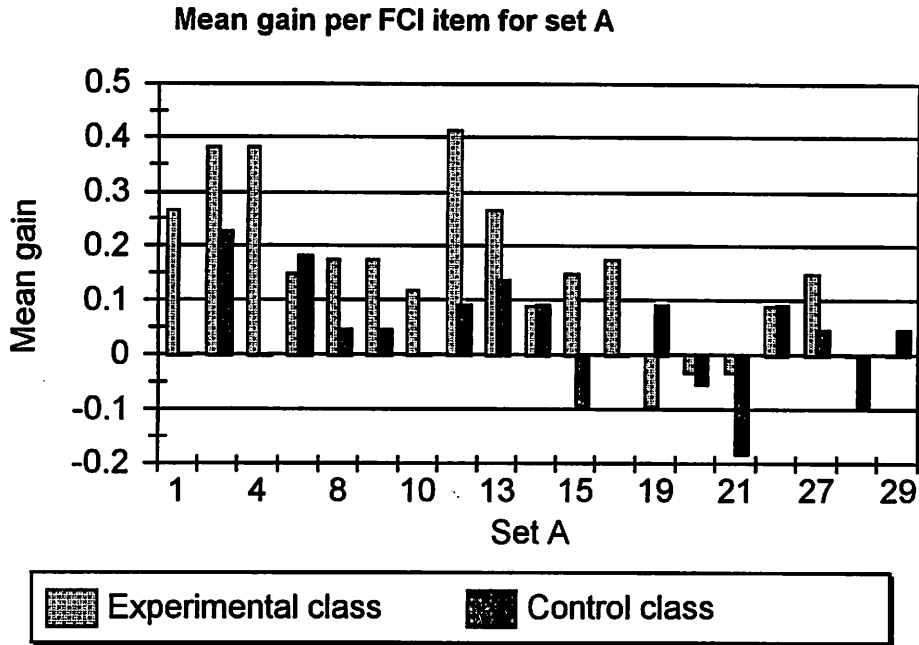
one-tailed t-test for independent samples:  $t(54) = 1.82, p < 0.05$ ). When we examined the difference between the mean normalized gain (0.24) for the experimental class and the mean normalized gain (0.06) for the control class on Set A, we found that the normalized gains were also significantly higher ( $t(54) = 2.69, p < 0.01$ ) for the experimental class while the difference was not significant ( $t(54) = 0.47, p < 0.1$ ) on the questions of Set B (the mean normalized gain is 0.06 for the experimental and the mean normalized gain is 0.01 for the control class).

Table 3  
Comparison of mean gains for Experimental and Control Classes

	Exp. FCI	Control FCI	Exp. Set A	Control Set A	Exp. Set B	Control Set B
$\langle G \rangle$ ( <i>sem</i> )	10.95% (1.91)	4.70% (1.25)	14.86% (2.95)	3.58% (2.12)	3.53% (2.30)	6.82% (3.24)
$\langle g \rangle$ ( <i>sem</i> )	0.19 (0.03)	0.10 (0.03)	0.24 (0.04)	0.06 (0.05)	0.06 (0.10)	0.10 (0.06)

**The impact of training on students' knowledge:** We wanted to be certain that any gains made by experimental students were not due to knowledge acquired during the training session. To this end, we examined the mean gain per FCI item in both classes (see Graph 1).

Graph 1



We found that the experimental students made noticeably greater gains than the control students on three particular items (#1, #4 and #11). We carefully examined the practice problems to see whether students could have acquired particular knowledge that would account for such a difference in the performance. There was no problem in the practice set similar to FCI item #1. There was a problem on topics related to each of items #4 and #11, although these were not covered in the training session and did not call for the students to answer the same questions as on the FCI. Nonetheless, we decided to rerun all the statistical tests after having removed items #4 and #11 from the data. All relevant statistics were still significant, indicating that content did not play a role in the training effect.

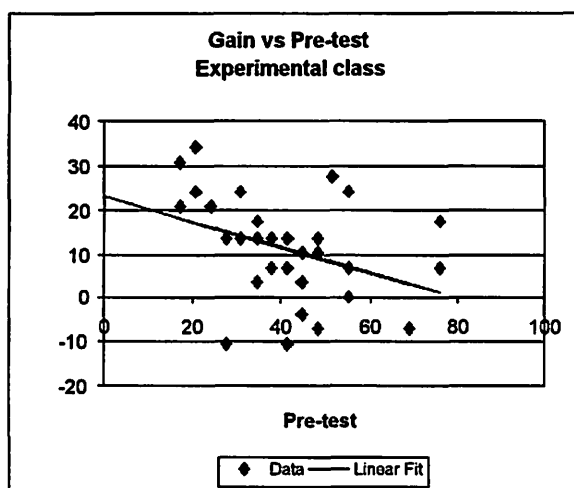
**Relationship between the gain and the pre-test:** We found that in the experimental class, gains,  $G_i$ , decreased with pre-test scores,  $Pre_i$ , with a correlation coefficient of  $r = -0.377$ . This relationship was reversed in the control class, where the gains increased with pre-test scores ( $r = 0.249$ ). To assess the significance of this result, we used Cohen's (1998) conventions and determined the power of significance<sup>3</sup> for both classes. We found that the power of significance is 55%, given the effect size and the number of subjects in the experimental class, and similarly 20%, given the effect size and the number of subjects in the control class.

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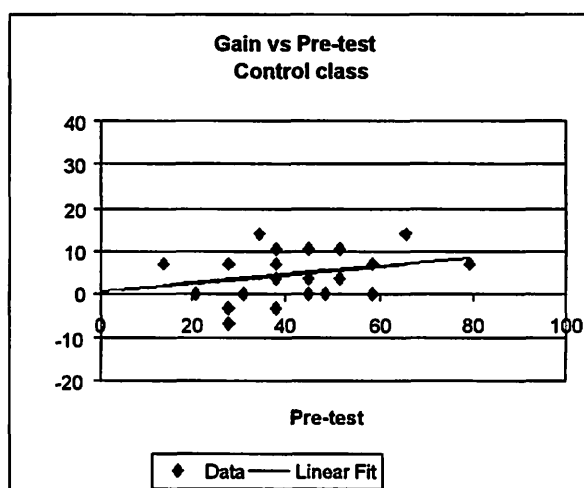
<sup>3</sup> Power of significance is a measure of significance which depends on the effect size and the sample size. When the effect size is large, the result may be significant even for a small sample size.

We also examined the correlations between pretest scores and gains,  $G_i$ , for items in Set A and in Set B. There was a marked difference in the correlation between gains and pre-test scores for Set A between the two classes: in the experimental group  $r = -0.694$  (power of significance 97%) and in the control class  $r = 0.48$  (power of significance 65%). For Set B items there was no correlation in the experimental class ( $r = -0.020$ ) and a low correlation in the control class ( $r = -0.235$ , power of significance 20%). For Set A, Graphs 2 and 3 are plots of  $G_i$  versus Pre, for the experimental class and control class, respectively.

Graph 2



Graph 3



**Effect of training in context of other studies:** Since both the pre-test and post-test were administered at the end of the course with only two weeks between them, we cannot compare our results to the usual pre/post-test data where the tests are administered at the beginning and end of the course. Even so, it is interesting to see our results with respect to those from the usual pre/post-test condition.

In his survey of physics courses, Hake (1998) used  $\langle g \rangle$  rather than  $\langle g_i \rangle$  as a measure of the average normalized gain on the FCI, where  $\langle g \rangle$  is the ratio of the actual average gain to the maximum possible average gain.

$$\langle g \rangle = \langle G_i \rangle / \langle G_{i_{max}} \rangle = (\langle \text{Post}_i \rangle - \langle \text{Pre}_i \rangle) / (100 - \langle \text{Pre}_i \rangle)$$

As Hake points out, theoretically somewhat lower random errors result if one takes the average normalized gain for a course to be  $\langle g \rangle$  rather than  $\langle g_i \rangle$ .

In Table 4, we show  $\langle g \rangle$  for our experimental and control classes with associated error  $\Delta \langle g \rangle$  which was computed using the same formula as the one used by Hake. For comparison we show  $\langle \langle g \rangle \rangle_{T\text{-ave}}$  and  $\langle \langle g \rangle \rangle_{IE\text{-ave}}$ , the average values of  $\langle g \rangle$  for fourteen

traditional classes and forty eight IE courses taken from the Hake survey.

Table 4  
Comparison with Hake's Data

	Experimental $\langle g \rangle \pm \Delta \langle g \rangle$	Control $\langle g \rangle \pm \Delta \langle g \rangle$	Hake survey $\langle \langle g \rangle \rangle_{T-ave} \pm sd$	Hake survey $\langle \langle g \rangle \rangle_{IE-ave} \pm sd$
FCI	$0.19 \pm 0.06$	$0.08 \pm 0.08$	$0.22 \pm 0.05$	$0.52 \pm 0.10$
Set A	$0.26 \pm 0.07$	$0.07 \pm 0.11$		
Set B	$0.06 \pm 0.08$	$0.10 \pm 0.09$		

### Discussion

**Equivalence of experimental and control classes** Students were not randomly assigned to experimental and control classes. However, there are indicators that the two classes were statistically equivalent. The high-school academic profiles of students in both classes satisfied the same narrow admission criteria (high school average between 65% and 70%) placing them in a remedial program. However, since students come from a variety of schools there is a possibility of a larger spread in their academic performance than is shown by their high school grades. The pre-test instrument (FCI) was the same for both classes and was administered under the same conditions. Consequently, the fact that the mean pre-test scores were statistically equal for the two classes is a strong objective indicator that the two classes were indeed equivalent. The pre-test scores were low in both classes (41.68% and 41.69 % for the experimental and control class respectively) as might be expected from students in a remedial program.

**Improvement in the FCI score.** Since the pre-test and post-test were administered within the last two weeks of classes, we expect a gain on the post-test to be due to both students' preparation for the final physics test and to pre-test exposure to the FCI. Indeed, both classes had significant gains.

**Effect of training on the FCI score** Both the gain and the normalized gain are significantly larger for the experimental class than for the control class. The training was effective in improving student performance.

We found that the mean gains per item were similarly distributed (Graph 1) with the mean gain decreasing with item number (which we suspect was due to fatigue since the students wrote the post-test immediately following the final exam). We conclude that it is unlikely that the training had an effect on the domain of knowledge. We therefore believe that the impact of the training was primarily on strategies students used to answer the questions.

This belief is further supported by the results for the two subsets. For Set A, the subset of items relevant to material taught in the course, there was a larger gap between the

mean normalized gain for the experimental class and the mean normalized gain for the control class as compared to the gap between those means for the whole set of the FCI. For Set B, the subset of items relevant to material not taught in the course, there was no significant difference between the gains and the normalized gains for the two classes. This indicates that the training was only effective when the students had appropriate knowledge to use with the strategy trained for.

We also found a significant effect of the training on the correlation between gains and pretest scores. We will limit our discussion to the results for Set A where the correlation coefficients are large and significant, and where we may be more confident that students have the conceptual knowledge of Newtonian concepts. There was a strong negative correlation between gain and pre-test score for the experimental class and a positive correlation for the control class.

If we consider the relationship between gains and pre-test scores, we anticipate three possible factors at work: the ceiling effect; student preparation; and, the training effect. In the analysis of our data we were able to discount the ceiling effect since only one student reached the ceiling and consequently, we don't expect that this factor plays an important role in the relationship between the gains and the pre-test scores. The second factor is the effect of student effort and preparation for the final test. If this factor were to play a role, we would expect gains to correlate positively with pre-test scores. The good students have a tendency to work harder and learn more in preparation for finals than poor students. Consequently, high scorers on the pre-test are likely to have higher gains. The third factor is the effect of training. Low pre-test scorers lack conceptual understanding, or strategic knowledge or both. The training should have an effect on those who only lack strategic knowledge and thus, fall into the trap of not using Newtonian concepts to answer FCI-like problems. Since the high pre-test scorers are likely to have both conceptual understanding and strategic knowledge, we expected that the training would be most effective for students scoring at the low end of the pre-test score range. If this factor were to play a role, we would expect gains to correlate negatively with pre-test scores.

The results show that the anticipated effect of student preparation was evident in the positive correlation between gains and pre-test scores in the control class. However, in the experimental class we see a strong negative correlation between the two variables. While we still imagine that there was an effect of student preparation on the correlation, it was outweighed by the impact of training. This indicates that there were students in the experimental class who lacked strategic knowledge and who improved their scores to reflect their true conceptual understanding. There was not much difference in gains for students who scored above 50% on the pre-test between the two classes. This indicates that the training had less impact on high scorers.

**Effect of Training in Context of other studies:** It is noteworthy that for the experimental class, the average normalized gain, where the gain was made over two weeks, compares favourably to the average for traditional courses (Hake survey) where

the gain was made over the entire period of the course. The gain does not compare to the gains made in the IE classes, which is not surprising since our IE intervention lasted only 75 minutes.

### Conclusions

Our experiment shows that there is a confounding factor in using the FCI as a measure of conceptual understanding. It also shows that it is relatively simple to provide students with strategies so that the FCI may more accurately reflect their knowledge.

Although we ourselves have used IE methods extensively in our classes for 20 years, the traditional method is the standard in the physics department. We were struck by the fact that even though the instructor of the classes in this study used traditional methods, his students showed their conceptual knowledge when they had the appropriate strategic knowledge. In particular, the instructor stressed Newton's Third Law, and the students performed relatively well on FCI items #2, #13 and # 14. We are inclined to agree with Griffiths (1997) who does not believe that "traditional methods are hopelessly flawed".

It seems to us one reason that FCI mean gains in IE courses are higher than in traditional classes is that IE course students are taught strategies for FCI-like problems. It would be interesting to know if the higher mean gains in IE courses are due to gains by all students or are mostly due to gains made by low scorers. If the latter is the case, then it may not be that IE courses are better than traditional courses in promoting conceptual understanding, but rather in providing skills for solving FCI-like problems. The question of whether traditional or IE courses are more effective pedagogies may not be resolved purely on the basis of FCI results.



## 5. QUALITATIVE VS. QUANTITATIVE QUESTIONS: WHAT'S THE DIFFERENCE

### Introduction

As was shown in the previous experiment, a short instructional intervention in problem-solving strategies improved students' performance on the FCI. The strength of the results was surprising, given that the instruction lasted only seventy five minutes. Our conclusion was that students had not learned new strategies during the instruction. Instead it appears that they discovered the usefulness of putting previously-learned strategies towards solving FCI-like problems. In view of this finding, we are led to ask the next logical question: What strategies were students using in selecting their answers on the FCI items? How were they thinking when they made their choices? Since quantitative methodology is an inadequate tool to explore these questions, we designed an appropriate qualitative study.

Furthermore, in the process, we wanted to contribute to the body of knowledge about students' misconceptions in physics. Question #23 on the FCI deals with several concepts: projectile motion, inertia, and frames of reference. We decided to use this particular question in response to Hestenes and Halloun (1985), who found that students perform poorly on it but were unable to identify in student interviews what particular misconceptions were at the root of their difficulty. We therefore developed physics-like and FCI-like versions of question #23, to be solved out loud by students during an interview. This interview would allow us to collect data on students' thoughts about both the quantitative and qualitative versions in order to identify consistent differences between their responses to them.

### Issues

The study of projectile motion is ubiquitous to all Mechanics courses. From a student's perspective it is a difficult topic on many counts. We will categorize common difficulties: translation of verbal statements; underlying physics concepts; and, problem-solving complexity.

**Word problems:** Students often have difficulty in translating descriptive verbal statements in physics problems into a visual image of the situation and pertinent events (schematic diagram). This is in part due to language usage in physics problems, which often relies on jargon and presents an incomplete verbal analysis of the situation, assuming that the reader will make inferences about meaning. For example, when referring to velocity, physics problems commonly use the words "initial velocity" and "final velocity". However, many students associate the adjectives "initial" and "final" with "before" and "after" the period of motion in question. Consequently, the statement "the initial velocity of a ball is 30 m/s" is conceptually difficult for many students to understand because they reason that the ball did not have a velocity "before" it moved, and questions like "what is the final velocity of a rock as it lands" often elicit a spontaneous response of zero (it has no velocity after it lands). In addition, students

also find it difficult to translate between verbal descriptions and symbolic representations of vectors. For example, many students find it difficult to translate the verbal statement "an object moving along the horizontal at 10 m/s" into its vector components of  $v_x = 10 \text{ m/s}$ ,  $v_y = 0 \text{ m/s}$ . These issues are relevant to FCI question #23, which presents students with a diagram. Diagrams are often used by physics teachers in the context of teaching problem-solving skills. Most students know that they have to draw a diagram, but it is not clear whether they do it because they are told to, or whether they truly see it as a problem-solving tool. In our experience, students' diagrams are often poorly drawn mechanistic reproductions of those learned in class. Whereas teachers work with diagrams while explaining solutions, students draw a diagram with some data at the beginning of the solution, and then don't use it any further. These difficulties with translating verbal statements into diagrams are also conversely seen with interpreting diagrams and forming verbal statements about the information they convey. Students often misinterpret the information represented by a diagram because of their lack of fluency in their symbolism and schematic conventions.

**Physics issues:** Students often confuse the concepts of velocity and acceleration, which causes difficulties when they attempt to solve problems. For example, in a problem stating that an object's initial velocity is non-zero along both the horizontal and vertical axes, the fact that the horizontal component of its acceleration is zero sometimes confounds students, who have a tendency to apply the acceleration in the equations for both the x-component and the y-component of the displacement. Conversely, in a problem where a ball rolls off a table with a given horizontal velocity, students often tend to apply that velocity in calculating both the vertical and horizontal component of the ball's motion once it's in the air.

FCI question #23 also involves an understanding of the concept of inertia. Most students at the college level have been taught the Law of Inertia and are able to state it. They can often use it to successfully explain certain phenomena observed in the physical world, for example, why people will move forward as the Metro train comes to a stop. They are even able to produce, on their own, examples of situations in which this law can be seen at work. They have difficulty, however, relating their understanding of inertia to problems similar to FCI question #23, in which an object is dropped from a moving body (airplane) travelling horizontally at some speed. They fail to see that if no force is applied to the object at the moment it is dropped the object will continue to have the same velocity as the aeroplane. One explanation might be that the layman understanding of the word "drop" implies no velocity, so that the image of an object falling straight down causes students not to process the problem in terms of the law of inertia. The other possibility is that they use their personal experience of dropping objects while inside a moving vehicle, which from their reference frame is consistent with the object falling straight down as well.

This brings us to another issue which might be at the root of student difficulties with FCI question #23: the Newtonian concept of velocity is relative. In our experience as physics educators, we have accumulated evidence that the concept of relative velocity

is very difficult to teach. This is not surprising, since historically this concept is relatively new, and clearly not intuitive. As a result, many Mechanics courses at the college level omit completely any discussion of the concept of the relativity of velocity. Since velocity is relative, and measured from a certain frame of reference, conceivably two people may be describing the motion of the same object and state two different velocities of the object. This nuance is often absent from everyday language and we simply state the velocity of an object without making reference to the observer. As a result, people often think of velocity as absolute.

Since each observer observes the velocity relative to himself, the observation of the path of an object is also relative to that observer. It is possible that students may not be aware that path is also a relative concept. Consequently, in their thinking about a problem they may use a different perspective than the one intended by its author. Even worse, since they may assume that the path is absolute, they may be jumping from one reference frame to another as they reason about the problem.

Another physics issue that confounds students' thinking about FCI question #23 is that the text of the question makes no reference to air resistance. However, air resistance plays an enormous role in the motion of falling objects, a fact that students know well from their experience in sports. They have noticed air flow as perceived from moving vehicles and the impact of air flow on the motion of falling objects on numerous occasions. The impact of air resistance and of air flow on the motion of objects is rarely (if ever) discussed in college level Mechanics courses, and leads to confusion about the effect of air on moving objects under various conditions. For example, students often interpret the "push" of air-resistance they feel out of a car window as "wind", and reason that "wind" will push an object being dropped from a moving body "backward" relative to the direction the body is moving in. Most of the reasoning about projectile motion is based on the assumption that there is no air resistance or flow. The reasons for making such an assumption are: first, in most cases we don't even have a mathematical model that adequately describes the motion of air particles relative to a moving object; and, second, in those cases when we do have a useful mathematical model, the relationships involve mathematics that students don't know. Since the discussion of air resistance is completely omitted in physics courses in the context of projectile motion, students don't develop any decision-making mechanism regarding when to include and when to exclude air resistance from their model.

**Complexity:** In high school, students develop a strategy for one-step problems. The task in such problems is to identify and appropriately label the given variables and the unknown, search for an equation which includes these variables, replace the values in the equation, and, solve. However, projectile motion problems involve a multitude of steps. The fact that students have to use vector algebra and solve for a set of equations with two or more unknowns also increases the complexity of these problems. In addition, the algebraic relationships between displacement, velocity, acceleration and time are often poorly understood, and, consequently, students have difficulty remembering them.

In view of all of the above mentioned difficulties, physics teachers often choose an algorithmic approach to problem solving and teach students rules like "velocity is positive and acceleration is negative on the way up and both the velocity and acceleration are positive on the way down" or "acceleration is  $-9.8 \text{ m/s}^2$ ". Students often memorize these rules without remembering the situations in which they are applicable. The algorithmic approach allows them to successfully solve certain kinds of problems, but curtails their development of a full understanding of the concepts. It lures students into thinking that they understand, when in fact they only have a good recipe. The algorithmic teaching style is then a source of frustrations for students when they don't understand why they are successful at solving some problems, while others, particularly those on exams, baffle them.

### Objectives

1. To study whether students use different approaches when solving a traditional physics problem as compared to an FCI-like problem, and if so, how. We anticipate that students:
  - a. might not use the same vocabulary when solving, out loud, the two types of problems;
  - b. might not refer to the laws of physics as frequently when solving FCI-like problems as compared to traditional problems;
  - c. might not use the same strategies for solving both types of problems.
2. To study whether students' conception of an observational frame of reference in the context of FCI question #23 is at the root of their difficulty with this problem.

### Methodology

**Participants.** The nine students participating in this experiment were enrolled in Introduction to College Physics. The course is offered as a bridging course to students who either had grades below 70% in their high school physics course, or who after failing their physics course in high school achieved less than 75% the second time they took it. All volunteers signed consent forms agreeing to participate in the experiment. Two of the students failed to do the post-interview and their pre-interview data were therefore eliminated from analysis. One additional student was eliminated from the analysis because her command of English was so poor that it was difficult to interpret the meaning of her statements.

**The experiment.** The aim of the intervention was to provide students with an opportunity to interlink with each other several concepts relevant to projectile motion, and to link them with the formulas they had learned. The intervention highlighted the differences in the shape and direction of the path of an object released from a moving body, depending on the observational reference frame and the presence of air-resistance. Specifically, students were to consider the path with regard to whether the object in projectile motion was being viewed from a stationary position or from the point of view of the moving body it was released from. Further, the intervention sought

to demonstrate that the ideal parabolic shape of the path can be altered by the effect of air resistance, adding another variable to take into consideration when predicting the shape of the path from either of the observational reference points.

The intervention was carried out over the course of two 75-minute class periods, and involved two components: computer simulations; and, a live demonstration. In an effort to maximize students' engagement with the material and subsequent understanding of the presented concepts, the instruction was interactive in nature. Students observed the simulations in pairs, and then together answered questions on exercise-sheets. They also presented their conclusions to the class and participated in class discussions with the teacher.

### Part 1 of the intervention

The first class period of the intervention was set in the computer lab. Each computer was loaded with the simulations, which the students were to observe in pairs. They were handed a worksheet on which to take note of their observations and conclusions, and received instructions regarding how to proceed.

**The simulations:** showed an object being dropped from a helicopter under the two observational reference frame conditions and the two air-resistance conditions, for a total of four separate simulation paths: the object's path as viewed from the ground under ideal "no air-resistance" conditions; the path as viewed from the ground under normal air resistance conditions; the object's path from the point of view of the pilot aboard the helicopter, under ideal "no air-resistance" conditions; and the path viewed from the point of view of the pilot, under normal air-resistance conditions. The computer screen showed both the helicopter and the object falling from it while in motion, with their respective paths being recorded behind them by a series of traces (dotted line). The distance between the traces was proportional to the helicopters' and objects' instantaneous velocity respectively, so that the dotted line showed not only the path of the object, but also its' acceleration.

**The worksheet (Appendix VIII):** had six exercises that the students were to do in pairs.

- The first section asked the students to observe the horizontal and vertical displacements of the object falling from the helicopter, and to draw some conclusions about the forces acting on the object. At this point the exercise made no mention of the position of the observer or of air resistance. The students were simply to observe what they saw in simulations 1-4 and consider it in terms of forces.
- The second section asked pairs of students to turn on the tape-recorder provided at the computer and to discuss their conclusions about the forces seen to be acting on the projectile object.
- The third exercise asked the students to continue recording their conversation, this time regarding their explanation of the shape of each of the four separate paths, and to take into account whether the perspective was from that of the pilot

or the bystander.

- The fourth assignment was to observe the series of simulations again, this time with an "observer's perspective" indicated by an eye, either on the ground (a bystander), or on the helicopter (the pilot). Observations on each path were again to be noted down.
- The fifth exercise was to repeat step one (draw conclusions about the forces acting on the object) in light of their experience with the observational reference frame.
- The sixth section asked the students to sum up what they had learned about the motion of the object in terms of 1) the path, 2) the forces acting on the object, 3) the importance of air resistance, 4) the influence of the position of the observer on the trace of the path, 5) how and when the path is a parabola.

### Part 2 of the intervention

The second part of the intervention took place in a regular classroom. The objective in this part of the intervention was to provide a link between problem solving strategies used in projectile motion problems and the observations of both the simulations and the live demonstration.

**Simulation:** In order to refresh the memory of students of the observations and conclusions made in the previous session, the simulations were presented for a third time, projected onto a screen at the front of the room for the whole class to watch together.

**Live demonstration:** The teacher asked the students to observe the path of an object (key chain) being dropped from a moving body (the teacher's hand while she was walking). A line was drawn on the floor, and the students were to say "now" when the teacher crossed it. At this point she would drop the keys and the students would observe the path of the keys and where the keys would land relative to the line as well as relative to the teacher, who kept walking. After group and then class discussions, the teacher and each group agreed that the keys had fallen in front of where the teacher had released them.

**Making Links:** After the above-mentioned refresher, the teacher drew the four separate observational situations and their respective paths on the blackboard, and explained how the separate paths related to the formulas that they had learned for projectile motion. A class discussion and a problem solving session ensued.

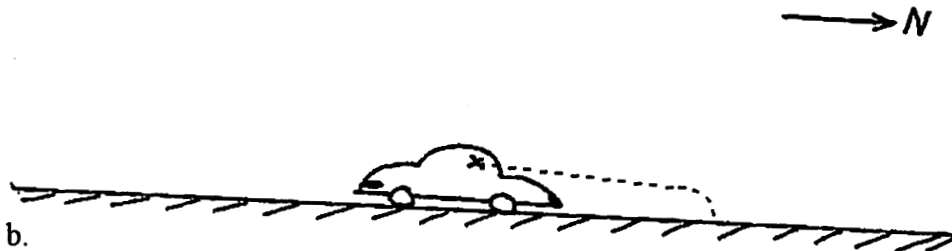
### Problem solving: contrast expert versus novice approach

Experts make automatic decisions when solving physics problems. Unlike experts, novices not have subsumed many detailed ideas into one coherent concept (Larkin & McDermott, 1980). Consequently, a the perceived complexity of a problem is reduced for experts, who recognize patterns as one piece of information, while novices struggle

through each step. The cognitive overload that novices experience while sifting through the problem-related information increases the possibility that they do not attend to every important detail, and thus make mistakes or get confused.

**FCI-like problem:** A driver of a car travelling North at a steady 30m/s drops an empty Coke can. The diagrams below show the car at the moment the can is released. The dashed lines represent possible paths of the Coke can. Discuss the path in each diagram in terms of how likely you think the Coke can is to follow that particular path.<sup>4</sup> Explain your reasoning in each case.

a.



b.



c.



d.



e.



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<sup>4</sup>Note that suggested paths a ... e correspond to the paths in FCI item 23. Neither problem shows the path of the moving vehicle after the drop.



### Solution of the qualitative problem.

The expert reads the first sentence and infers that:

- he is reading a physics problem since physics vocabulary is used to describe the motion;
- the car moves along the horizontal at a constant velocity;
- the reference frame used here is that of a ground observer since only in that reference frame will the car have velocity;
- the coke can has an initial velocity equal to that of the car as the Law of Inertia is applicable here since no force is applied on the coke can when it is dropped, *i.e.*,  $v_x = 30$  m/s;
- the vertical component of the velocity  $v_y$  is zero;
- the problem is stated in the context of the Introductory course in Mechanics and, thus, air resistance is not to be taken into the account.

The next sentence indicates to the expert that the diagram only shows the position of the car at the moment the coke can is dropped. The subsequent motion of the car is not shown in the diagram. The last sentence of the problem statement indicates to the expert that the path of the coke can after the drop, but not that of the car, is shown in the diagram. If the path of the car were shown it would be a horizontal line towards right as indicated by an arrow pointing North.

Experts recognize that their task is to select the path of the coke can that looks like that of an object in projectile motion. Since the initial velocity has a non-zero horizontal component and a zero vertical component, they select a path which

- is drawn to the right (as indicated by the direction of motion of the car and the can)
- has a horizontal tangent at the point of drop (since  $v_x \neq 0$  and  $v_y = 0$ )
- is a parabola (since the function  $y(x)$  which describes for the path is a quadratic function) since the coke can accelerate downward while the horizontal component of the can's velocity remains constant.

Note that most of the experts analysis described above is done subconsciously and only the last three criteria will be clearly spelled out.

### Student solution of the qualitative problem

**Pre-instruction interviews:** The pre-instruction interviews revealed different patterns of thinking among students. Don, an exceptional student, mentioned his high school instruction in physics when solving the problem and thus, obviously saw the connection between this problem and physics as experts would. Similarly, without evidently thinking about it he assumed that there was no air resistance. He chose the correct path. Don had difficulty communicating his thoughts. He was unable or unwilling to express whether he has formulated any expert-like criteria for path selection. When pressed as to why he eliminated path d he said: "I know it wouldn't just fall, it has its

momentum" Otherwise he kept saying "I think ...", "... it doesn't make sense", "I have a feeling ...". When the interviewer said "you are basically saying that's a feeling you can't express..." he replied "It's kind of based on things I learned last year" and continued to recall "... she dropped a rock out of a plane, and it continues, it's always under the plane". It seems that he understood the concept of inertia but did not have the vocabulary to communicate his ideas.

Karl interpreted the question differently although he understood that it was a physics problem. He assumed that his task was to describe a set of forces acting on the coke can for each example of the path. In his description, he was the only participant who demonstrated having a known common misconception: a moving object exerts a force. He talks about "...the speed of the force of the car ..." and "the force of the car is going by the speed of the car." This misconception has been associated with a pre-Newtonian mental model and it is believed to be prevalent among students. It is surprising that we found only one student among all the participants who had this misconception, and even then, only in his pre-instruction interview did he espouse it. In the end, Karl chose path e as the most likely.

The remaining students approached the problem differently in the pre-intervention interviews. None of them made any link to their previous physics instruction. Instead, they were recalling their experience: "...it's pretty windy, it would not go that way ...", "...Everybody has done it before (throw an object out of a moving vehicle)..." or "...when I throw the can the car is moving so the can is going behind me ...". Based on their experience, all students chose path e.

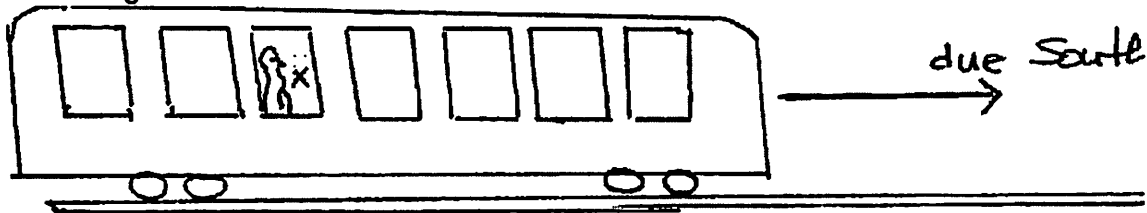
***The post-instruction interviews:*** In the post-instruction interview Karl changed his opinion. He selected as possible choices of path b and c because as he put it "the coke can is moving straight down (pause) so it has dropped (pause) some kind of (pause) without any forces moving, without any forces on it except gravity." His expressions, e.g., "...will go slowly straight down like a curve" indicate either incoherent thinking pattern or poor language skills, or most likely both. Forced to make a choice between the two possibilities, he said "I think the most common forces would be path b or c because it has only moving without any forces or only one force." The interviewer pressed further: "Pick one" and he replied "OK, b without any forces on it". Here he may have a fragment of a correct idea - if an object moves along a straight line one may conclude that possibly, but not certainly, there are no forces acting on it. Although his English is unclear, he clearly connects force with the path incorrectly.

In the post-intervention interview with Nina we saw a struggle. She immediately connected the problem to the intervention. She began with "The car is going forward this way - well, logically, the coke can should go backwards, because with class with the projectile motion ...". She described the simulations and continued "...the plane is going this way, and he dropped the package from the plane. The plane kept seeing it as it was straight underneath, but if it is straight underneath then it means the package is going forward - it doesn't make sense...". She recalled her experience "...if I dropped

a can and I'm walking, it will fall behind me - so that's the way it should be...". She doubted "...But that totally differs what we studied ... so many people (referring to her classmates) saying, and we all agreed with it ... he saw it going forward". She concluded "Based on what we studied, it should be going forward. Based on what I think about it, it should be going backwards. I say e". It is interesting to note that while solving the quantitative problem she spontaneously recalled her solution of the qualitative problem and wanted to change e. She recognized she is having difficulties reading the diagrams in the qualitative problem. It appears that she had a coherent naive model and that she also formulated another coherent model in class. She struggled with the contradiction and was unable to resolve it.

### Expert solution of the quantitative problem

*A passenger dropped an empty beer bottle from a train travelling at 40m/s headed due south. The bottle was dropped from a point 2 m above the ground. Determine the horizontal distance the beer bottle travelled before landing.*



Experts will read and analyse this quantitative problem in a similar manner to the previous qualitative problem, *i.e.*, neglect the air resistance and solve it by using the equations for projectile motion in the reference frame of the observer on the ground with the vertical axis pointing down, the horizontal axis pointing South and the origin 2 m above the ground. They recognize that the components of the initial velocity of the bottle are  $v_x = 40 \text{ m/s}$  and  $v_y = 0$  because the Law of Inertia is applicable in this situation. Substituting  $\Delta y = 2$  into the equation for vertical displacement  $\Delta y = \frac{1}{2} 9.8 t^2$ , they solve  $2 = \frac{1}{2} 9.8 t^2$  for  $t$  and find  $t = \sqrt{0.4} \text{ s}$ . Then from  $\Delta x = v_x t$  they find the horizontal distance to be  $40 \sqrt{0.4} \text{ m}$ . Note that to the expert the solution has only a few simple steps.

### Student solution of the quantitative problem

With the exception of three students, Anthony, Carl and Don, students did not solve the quantitative problem. Remaining students did not remember the equations of projectile motion in both interviews. Interestingly, they all assumed that the initial velocity of the bottle was 40 m/s. In the pre-instruction interview only three students assumed the velocity to be opposite to the train velocity, while the remaining students assumed that the bottle moved horizontally in the same direction as the train. In contrast, in the post-interviews all students assumed that the bottle moved in the same direction as the train, as indicated by their own diagrams. When they were given the equations of projectile motion in the post-instruction interview students still had difficulty solving the

problem. They did not know how to find the components of the initial velocity, had difficulty distinguishing between velocity and acceleration and velocity and displacement. We emphasize that all students (including Carl who selected the straight diagonal path and Anthony who selected the straight vertical path in the qualitative problem) drew a diagram as they solved the quantitative problem which resembled path c of the qualitative problem.

It should be noted that the instruction really did not focus on the equation of projectile motion. Furthermore, it should be noted that the interviews took place two weeks before the final exam. It is obvious that students did not study the subject before the interviews. The final examination included a problem similar to the quantitative problem and most of them were able to solve it correctly then.

### Discussion

Although one could say that students were equally unsuccessful in solving both qualitative and quantitative problems, we did see a difference in their approach to the two. In the pre-instruction interview, while all students recognized and attempted to use the Newtonian model to solve the quantitative problem, most students used their personal experience in solving the qualitative problem. During the post-instruction interviews, even though students referred more to wind, air resistance and what the driver or the person on the ground sees than they did in the first interview, this shift was more evident for the quantitative problem. Only a few of them used physics vocabulary in the discussion of the qualitative problem in the second interview.

In the pre-instruction interview students were almost uniformly convinced that path e is the path followed by the coke can. They made this decision based on their personal experience. It should be noted that path e is the correct choice from the point of view of the driver if air resistance is taken into consideration. That is, the naive physics model makes the same prediction as the Newtonian model in the reference frame of the driver if air resistance is not neglected. The problem with the student's choice of this path in this situation is that they were not aware their assumptions. A more varied picture emerged in the post-interview. Some students struggled to reconcile their naive model with the Newtonian model of this situation as observed from the point of view of the ground, and with or without air resistance depending on the student. Most students based their reasoning solely on their interpretation of the diagram. Repeatedly they argued that if one drops an object from a moving car, it cannot get "ahead of the car". This misinterpretation is striking if one considers that their own schematic diagrams in the quantitative problem were the same as the diagrams in the qualitative problem in that they did not show the path of the train, and the bottle path moved "forward". It is puzzling that they were not aware of the fact that they took conflicting views of the path in the qualitative and the quantitative problem. We pointed out the discrepancy to them during the discussion after the interview and overall students needed help to resolve the contradiction.

It is also apparent that the intervention, despite the fact that students felt that they understood the message of the intervention, or as one student put it "we all agreed", did not dislodge their naive model, nor did it provide them with an appropriate conception of the Newtonian model that would explain their personal experience. Similar findings are reported by McDermott (1991). Only a few students used the model in their reasoning, and often they were confused by it. When asked about their avoidance of using what they were taught during the intervention in the discussion after the post-interview, students cited various reasons: e.g., different situation, lack of confidence, etc., while at the same time claiming that during the intervention they had felt that they understood it. They appeared to be embarrassed by this. In their discourse students indicated that they consider air resistance or wind as a factor, but that the intervention did not clarify the role of the air resistance sufficiently. While many used the driver's reference frame in the solution of the qualitative problem, all students invariably took the ground reference frame in the quantitative problem. They were not aware of the fact that they were using a different reference frame in the two problems, although some students made specific mention of the position of the observer.

The intervention was effective in showing that reference frame has an impact on the perceived path of an object in projectile motion, but students were not able to transfer the knowledge and apply it to this situation.

Whenever they discussed the Newtonian model, it was apparent how fragmented students' knowledge remained, despite the intervention. On many occasions the terms force, velocity and acceleration were used inappropriately. Some students felt that the interview itself disturbed their thoughts and this could explain why their discourse was incoherent. On the other hand, given the nature of their difficulties we suspect that their inability to express their thoughts reflected a fragmented and incoherent knowledge structure. Many students demonstrated that they could use the concept of inertia but that their knowledge was fragile in the sense that they doubted their own conclusions about the velocity of the coke can or bottle and frequently contradicted their previous assertions.

### Conclusion

At this time our major conclusion must be that this is a study in progress. We have uncovered a number of interesting phenomena in the interviews, and on that basis we need to design a new intervention and a new protocol for the interviews in order to obtain a better appreciation of students' understanding of the complex phenomena involved in FCI question #23.

We found that on the cognitive level, students tended to use the naive model in the qualitative problem, thus confirming our findings in the FCI experiment. We also found that students perceive both problems as very complex. While experts eliminated the issues of air resistance and the frame of reference from conscious consideration, students stumbled on them constantly. The doubts students had about the initial

velocity of the coke can or the bottle added to their general unease. Similarly, in the quantitative problem, the components of the initial velocity, which are immediately evident to experts, caused great difficulty for students. Furthermore, students were frazzled by the diagram, which appears perfectly clear to experts. It was also found that students do understand, to some extent, the concept of inertia but that their understanding is tentative.

We also found that students expressed their thought less coherently when they talked about the Newtonian model, as compared to their discourse when they were using their own naive model. The frequent contradictions, particularly in "physics talk" of students, which sometimes occurred within a few sentences, are testimony to doubts, confusion and fragmented knowledge. The fact that some students found it difficult to talk while they were thinking, and the fact that many of them had poor language skills makes the analysis of the interviews particularly difficult.

In a follow-up study we intend to continue our usual practice, not done in this experiment, and provide students with incentives to perform well. Furthermore, the intervention did not include a practice problem set. Consequently, students were unprepared and did not reflect on the issues raised in the intervention during the time that elapsed between the intervention and the second interview. In the follow up experiment we intend to generate a practice problem set as well as performance incentives in the design.

The selection of participants will be include language skill criteria, and the students will be interviewed three times. The first time will be a practice interview session so that the students have an opportunity to practice thinking aloud. Only then will we run the pre-instruction and the post-instruction interviews. Furthermore, the interviewers will follow a script derived from the data we collected so far. In this manner we will be able to compare different students' discourse, and to verify some of our findings. The intervention itself could be improved by including instructions to the students that they must sketch diagrams of motion in various situations, and then discuss their diagrams.

## 6. SUMMARY

Despite the fact that a scientifically literate work force is becoming increasingly more critical to our technologically based society and world economy, the science curriculum in our colleges continues to be ineffective in achieving its aims. It has been found that students who study science fail to integrate their knowledge fragments into a larger understanding, and many of Quebec's students have serious difficulty completing a DEC or using their disjointed knowledge in subsequent endeavours.

In an effort to address these problems, we began a course of research to study and develop classroom teaching strategies and testing instruments that focus on integrating knowledge. Our work was conducted in the domain of physics, particularly in Mechanics courses, and is founded on the theoretical perspectives of learning and knowledge structures posited by conceptual change theorists. Investigators (Novak, 1988) believe that a knowledge structure is a web of inter-connected cells or nodes, each containing a concept. Gentner and Stevens (1983) coined the term "mental model" to describe such a sub-branch, including its connections to the rest of the branches within a knowledge structure. In attempting to describe how knowledge structures change, many theorists (Posner, Strike, Hewson, and Gertzog, 1982) borrow from Piaget (1954) and posit the dual processes of assimilation and accommodation. For example, one creates a mental model as one learns about an object and makes connections at this new "node" to other mental models. This process is called assimilation. If the new mental model provides information that requires a new way of thinking about the world, accommodation may take place. Accommodation, or "conceptual change" is a process in which the current organizing scheme of the knowledge structure is re-examined and replaced by a new scheme.

Students in science courses often have ill-structured prior mental models, which often contain misconceptions (e.g., Clement, 1982; Styer, 1996). Unlike that of expert models, ill-structured mental models have few relationships to other concepts within a knowledge structure (fragmentation of knowledge), some relationships may be wrong or the entire organization of concepts may not resemble that of experts' knowledge structures (misconceptions).

The objectives of our research can be outlined as follows:

- 1) design a classroom intervention for conceptual change;
- 2) develop an instrument to measure conceptual change within the classroom context;
- 3) examine factors that confound the measurement of conceptual change;
- 4) study how students think (differently) about qualitative versus quantitative physics problems.

The methodology of our research varied with the objectives and was a blend of qualitative (semi-structured interviews) and quantitative (quasi-experimental research designs).

## 1) Designing a Classroom Intervention for Conceptual Change

This original objective of our research program was to design a classroom intervention for a physics course in Mechanics that set appropriate task and classroom conditions so as to promote conceptual change moving students from a common-sense understanding of the physical world to a Newtonian-based mental model, and then to assess whether the intervention was more effective than traditional instruction in promoting deep understanding.

We designed an intervention that, based on conceptual change literature, should fulfill the criteria for promoting conceptual change, and then an experiment that to test the intervention. The experiment compares control students who received a session of interactive instruction on the Newtonian Model of a particular physics concept to those receiving a session of interactive instruction that would allow them to contrast their naive model of the physical world (misconceptions) to the Newtonian model and elaborate the connections between these models. However, our quantitative measure of conceptual change proved to be unreliable, so the results could not be validly interpreted. This study will be run again when development of an instrument that measures students' conceptual change is completed.

## 2) Development of an Instrument to Measure Conceptual Change Within the Classroom Context

There is no measurement tool that can be used in the classroom context to assess the understanding of students concerning the concept of inertia and the relationship between force and change of velocity. Conceptual change is currently assessed qualitatively through interviews and questioning, which is an impractical procedure for instructors to use on a casual basis in their classes. We attempted to develop a template that could be adapted to any content domain, and which instructors could use on an everyday basis to assess whether their students had developed an appropriate conceptual understanding of a topic.

The design of the template that we experimented with flows from the idea that there are links between concepts, and that some concepts are more closely linked than others, *i.e.*, some have direct links and some are linked only via one or more intermediate concepts. The idea is that instructors would provide a list of concepts and students would be required to rank the proximity of concepts. On the basis of their ranking, a student concept map is produced by software, and then the concept map is evaluated, again by software, by comparing it to a concept map generated from an experts ranking of the same concepts. The generation of the concept maps and subsequent comparison and evaluation were to be done by a software package called Pathfinder. Our template, called the Motion Questionnaire, includes a precise definition of the concept of proximity based on logical reasoning. Although we created a template that is easily adaptable across disciplines and areas within a discipline, and easy to administer, in the course of our testing we discovered that students have difficulty with both the qualitative question



format and the use of our definition of proximity. Thus, their scores are unreliable measures of their conceptual understanding. We identified poor skills of students in formal logical reasoning as the underlying cause for the difficulty with our definition of proximity. We intend to continue development of this promising method for measuring conceptual understanding and experiment with training students in reasoning logically since we believe this will provide other benefits in their studies of science.

### 3) Experiment: Does the FCI Measure Conceptual Change or Does the Format of Questions Confound the Scores?

Based on the results of our work to develop a measure of conceptual change, we began to question whether a standardized instrument can be validly used to measure conceptual change. Both the Motion Questionnaire and the FCI, an instrument used widely to measure students' conceptual understanding of the Newtonian concept of force, do so on the basis of qualitative questions. However, interviews with students revealed that they have trouble understanding what is expected of them, and how to solve problems stated in the qualitative multiple-choice format. We hypothesized that the FCI performance of students would improve as a result of a short training session teaching them to recognize the novel question format as physics (without teaching the material), and thus to apply their physics knowledge and strategies learned in physics to solve such questions.

Our experiment shows that there is a confounding factor in using the FCI as a measure of conceptual understanding. The training session improved the performance on the FCI of students in the experimental class as compared to the performance of control class students. It is noteworthy that the impact of the training session on the performance of low-scoring students was larger than that on high-scoring students. The results of this study are of particular importance to instructors in traditional lecture based classes who wish to use the FCI to assess their students understanding of Newtonian physics. It indicates that the performance of their students on the FCI is not necessarily an accurate reflection of their conceptual understanding. Furthermore, it shows that it is relatively simple to provide students with strategies so that the FCI may will more accurately reflect conceptual understanding.

### 4) Study: Do Students Think Differently About Qualitative and Quantitative Physics Problems?

Students difficulties with qualitative problems and the results of the previous experiment suggested that students think differently when posed qualitative problems versus quantitative problems. We were led to ask the next logical question: what strategies were students using in selecting their answers on the FCI items? How were they thinking when they made their choices?

We performed a qualitative study in which students were asked to think aloud as they solved two conceptually identical problems, one formulated qualitatively (FCI-like), and

one formulated quantitatively (physics-like). We first developed FCI-like and physics-like versions of question #23 in the FCI, and then collected data on the thoughts of students solving them.

In our study we found that, as expected, students tended to use a naive model when faced with a qualitative problem, thus confirming our findings in the FCI experiment. We also found that students perceive both problems as very complex. While experts eliminated such issues as air resistance and the choice of frame of reference from conscious consideration, students consistently stumbled on these issues. The doubts students had about the initial velocity of a coke can dropped from a moving car or a bottle dropped from a moving train added to their general unease. Similarly, in the quantitative problem, the components of the initial velocity, which are immediately evident to experts, caused great difficulty for students. Furthermore, students were frazzled by the diagram, which appeared perfectly clear to experts. It was also found that students do understand, to some extent, the concept of inertia, but that this understanding is tentative. We also found that students expressed their thoughts less coherently when they talked about the Newtonian model as compared to their discourse when they were using their own naive model. We attribute this effect to a fragmented knowledge structure.

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## Appendix I

Notes distributed in the experimental class

Scattered throughout the text are questions. When you reach a question, answer it before you read further.

## Models in Physics

In class it is easy to think that all the laws of physics that you are learning are absolutely true, but this is not so! The laws of physics are a human attempt to describe nature but often only do so within a limited range of condition. Laws are based on *models* which scientists have developed to try to understand physical processes.

*A model is a system of assumptions and deductions that are presented as a mathematical description of a system.*

No model is ever perfect. A model is used to suggest new experiments but if it fails to explain the observations, it must be modified or replaced.

For example, you have studied the motion of a falling object. On the earth, Newton's Law of Gravity does a good job of describing such motion and it also does a good job of describing the motion of the Moon as it "falls" in orbit around the earth and the motion of the planets as they orbit the Sun. However, in the early years of this century Einstein postulated a new model called General Relativity to explain gravity. General Relativity predicted a different orbit for Mercury than was predicted by Newton's Law and a detailed study of this orbit confirmed the Einsteinian prediction. General Relativity also predicted that light would be deflected by gravity and indeed astronomical observations have shown this to be true. The deflection of light by gravity lead to the idea of "Black Holes", a current hot topic in cosmology. Einstein's theory of gravity is unlikely to be the last word in our attempt to describe the force that animates our universe. Today cosmologists are working away at new theories so stay posted for upcoming developments.

When you are growing up, you make your own models or pictures to explain the world around you. Then in your physics course, you are given new models to learn. The problem is that you have lived with your old models for a long time and you often fall back on them when trying to understand or solve a physics problem. In this set of notes we are going to compare two models that describe motion. The first is a "commonsense" model that may have become part of your thinking as you grew up and could be difficult to dislodge. The second is the Newtonian model that you learned in high school physics class. Many students use a mixture of the two models when they solve physics problems. While the "commonsense" model can be used to give the right answer in some cases, the Newtonian model has a wider range of validity. In the same way, Newton's Law of Gravity still works in some cases while General Relativity has a wider range of validity. We believe that if you confront the fact that you need to completely replace your comfortable model with an improved version, you will have more success in understanding motion.



## "Commonsense" Model

We will begin with a discussion of commonsense ideas which work to describe some phenomena but not others. In general, the "commonsense" model allows us to function in the world pretty well as long as we are dealing with objects at rest. Look for the warning "*Watch out!*" which will alert you to cases where commonsense ideas do not predict actual behaviour.

**"Commonsense" Idea #1:**            ***"The natural state of a body is to be at rest."***

Commonsense would have us agree with Aristotle (circa 400 B.C.) that the natural state of an object is to be at rest with respect to the earth. After all it takes an effort to move. We must use energy to walk or run, we must step on the gas to drive a car. Our "commonsense" model says that if there is no force acting on an object, it must be at rest.

*Watch out!*    *This is not the **complete story.***

*Watch out!*    *Since it seems natural for an object to be at rest, students often think that in any physics problem, both the initial velocity and the final velocity of the object are zero. For example: An object is thrown off a balcony with a velocity of 5 m/s straight down and falls 30 m to the ground. What is its final velocity? It is easy to think that the object starts at rest and ends up at rest since in fact it does. There are really three stages of the motion, the first, where the object is launched, the second where the object is in free fall, and the third, after the object hits the ground. In Mechanics we often restrict the problem to the free fall motion so that for this stage, the initial velocity is 5 m/s down and the final velocity is 25 m/s down.*

**"Commonsense" Idea #2:**            ***"Motion implies a force."***

From our everyday experiences, we think that if something is moving there must be a force acting on it. We know about applying pushes and pulls. We notice that in order to bicycle at a constant speed, we must keep pedalling, otherwise the bike will eventually stop. We also know that gravity pulls everything down even though we don't think about what causes gravity. We notice that motion is started by either a force in direct contact with an object or by gravity acting on the object. Our "commonsense" idea is that if an object is moving, there must be a force acting on it.

A moving object doesn't stop moving the moment we stop applying a force to it, for example a bike doesn't stop the moment we stop pedalling. What is the mechanism that keeps it going for a while? Commonsense has led to the idea that an object set in motion has a "momentum" or internal force that keeps it moving. When this "momentum" is gradually used up, the object slows down and comes to a stop. For example, a person who pushes a toy car to set it rolling along the floor gives

"momentum" to the car, and it is this "momentum" that keeps the car moving after it is no longer in contact with the person's hand. As the "momentum" is used up by friction, the toy car slows down and stops.

Even if this idea of "momentum" works to justify why an object keeps moving after it has been pushed, it is often not extended to an object that is carried then released. For example, if a food package is dropped from a plane, it is easy to think that the package will drop straight down to the ground. Actually when a plane drops a food package, it must release the package before it reaches the target as the package has horizontal velocity when it leaves the plane. The moment the package leaves the plane, it has the same horizontal velocity as the plane, but as the package continues, it slows down because it no longer has an engine to counter air resistance. To an observer on the plane, the package falls behind a bit as it falls. To an observer on the ground, the package follows a near parabolic path since it has horizontal velocity until it hits the ground.

*Watch out! Any object that is carried retains the velocity of the carrier when it is released.*

**"Commonsense" Idea #3: "Motion is in the direction of the force."**

A common belief is that an object will always go in the direction of the force that is applied to it. This is because we usually think of exerting a force on an object at rest, in which case the resulting motion is in the direction of the force. But if a force is exerted on a moving object, we will see that the resulting motion may not be in the direction of the force.

*Watch out! We will see that the motion of an object is not necessarily in the direction of the net force on it.*

## **Newtonian Model**

The Newtonian model has proved successful in describing everyday phenomena. It breaks down at the outer limits of our observable universe, that is 1) at high speeds, 2) atomic dimensions, 3) celestial scales.

### **Newton's First Law**

Until the Renaissance, the ideas of the "commonsense" model were used to describe motion. Galileo (circa A.D.1600) had the imagination to propose a new picture of motion. He suggested that if an object is moving without anything touching or disturbing it, then the object will go on forever coasting at uniform speed in a straight line. His idea was that it is just as natural for a body to be moving in a straight line at a constant speed as to be at rest. He observed that if an object is given a push on a rough surface it will quickly come to rest but if a smooth object is given a push on a

smooth surface, it will slide for much longer. He imagined an idealized situation where a perfectly smooth object is given a push on a perfectly smooth surface and slides forever. His genius was to make an abstraction of a world without friction where an object once moving would only slow down if something disturbed it. This allowed him to think of friction as a retarding agent.

Newton (circa A.D. 1700) took Galileo's work one step further with the idea that the only way to *change* motion is to use a force. Newton's first laws of motion restates Galileo premise:

**Law I:**        **A body continues in its state of rest or of constant speed in a straight line as long as the net force acting on it is zero.**

*Watch out! This is quite different from the "commonsense" model. To illustrate, consider the motion of a puck once it has left a hockey stick. In the "commonsense" model, it is necessary to explain why the puck keeps moving. In the Newtonian model it is natural for the puck to keep moving, but it is necessary to explain why it slows down and stops.*

You have learned that velocity describes both speed and direction. We can rephrase Newton's first law in terms of velocity: *A body will continue in a state of rest or constant velocity if there is no net force acting on it* i.e. there will be no change in its speed or direction.

*Watch out! Note that there is a difference between constant speed and constant velocity. A car that rounds a corner at a constant 100 km/hr has constant speed but not constant velocity because the direction of its velocity is changing. A force is required for this change of direction.*

According to the first law, when we are pedalling a bike at a constant velocity (i.e. constant speed in a straight line), the force that propels the bike forward is equal and opposite to the force that retards it. There is no change in speed because the net force on the bike is zero. When we stop pedalling, the retarding force slows the bike down until it stops.

*Watch out! If you are given a physics problem where you are told that an object has a constant velocity, you are really being told that the net force on the object is zero! For example, if you are told that "for one section of the course, a downhill racer has a constant velocity of 80 km/hr", you are really being told that there is no net force on the skier.*

**Question 1.**

It takes a force of 5 N to keep a book sliding on a table at a constant velocity. What is the frictional force acting on the book? (Do not continue until you have solved this question.)

Now let's look at what it means to be at rest or moving at a constant velocity. Usually, when we say an object is at rest, we mean with respect to the earth. It is amazing to think that even though we feel that we are at rest, the earth is whizzing through space. The earth has an average orbital speed of 30 km/s with respect to the Sun while the Sun has an average orbital speed of 200 km/s with respect to the centre of our Milky Way Galaxy. Alpha Centauri is moving away from us at 22 km/s but space aliens in Alpha Centauri would say that the Milky Way is receding at 22 km/s from them. Whenever we describe a velocity it is with respect to some **frame of reference**

A coordinate system that is moving at a constant velocity is called an inertial coordinate system. A train, moving at a constant 50 km/hr North with respect to the earth, is an inertial coordinate system. If we are sitting in a soundproof, windowless room aboard such a train, we cannot tell the difference between the train at rest, the train moving at a constant velocity of 50 km/hr North, or the train moving at a constant velocity of 100 km/hr South. In fact, if we have no contact outside the room of the train, there is no experiment that we can perform that will enable us to determine the speed of the train. However, we can tell when the train starts as we feel the back of the seat pressing against us. We can also tell when the train speeds up, goes around a curve, slows down or stops, that is, we can tell when there is a change in velocity.

**Question 2**

- a) The train screeches to a stop. Use Newton's First Law to explain what happens to your body.
- b) The train goes around a curve counterclockwise. Use Newton's First Law to explain what happens to your body.

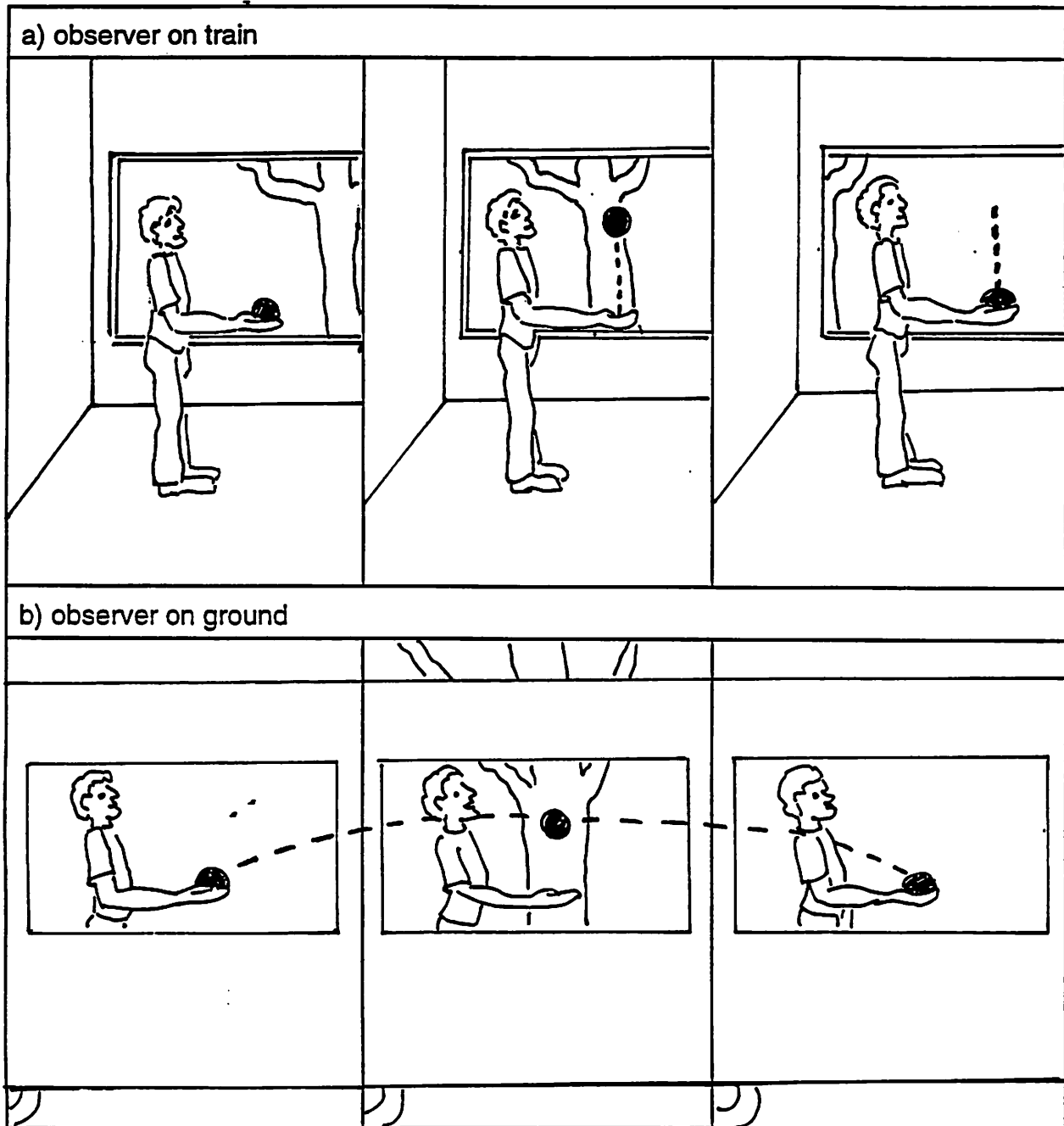
Even when we travel on a plane at high speed, we have no feeling that we are travelling at 900 km/hr as long as the speed of the plane is constant and the plane travels in a straight line. When the blinds are down so that we can't see out the windows, there is no way for us to measure the speed of the plane from inside. It's only when the plane takes off, lands, changes direction, or hits an air bump that we feel anything. We can only detect a change in the velocity of the plane *i.e. a change in its speed or a change in its direction of motion*. When the velocity changes, we are no longer in an inertial coordinate system.

**Watch out!!** *The "commonsense" model distinguishes between a state of rest and a state of motion. The Newtonian model distinguishes between a state of constant velocity (which includes zero) and a state of change of velocity.*

**Question 3.**

Suppose you are sitting in a soundproof, windowless room aboard a hovercraft. Which of the following can you detect from inside the room - a) horizontal acceleration, b) change of direction, c) speed of craft relative to ground, d) vertical acceleration, e) state of rest with respect to ground?

When you hold a magazine in your hand, the speed of the magazine can be given with respect to the plane or with respect to the ground. With respect to the plane, the speed of the magazine is zero, yet the speed of the magazine relative to the ground is 900 km/hr. Similarly if you are holding a ball on the flat car of a train travelling at 80 km/hr, the speed of the ball relative to you is zero but the speed of the ball with respect to the ground is 80 km/hr. If you throw the ball straight up in the air, to you the ball goes straight up and down while to an observer on the ground the path of the ball is a parabola.



Since the ball is at rest with respect to the train, it is travelling at the same horizontal speed as the train. The combination of its horizontal and vertical motions looks like a parabola to the person on the ground.

## Question 4.

Kim is sitting in a train playing with a toy ball. She is so absorbed in her game that she doesn't notice that the train is moving forward with speed 20 m/s, she thinks that the train is still stopped in the station. According to her, she's throwing the ball straight up and catching it in the same place. Joe is standing on the ground and he observes her game. a) If the ball takes a total of 1.5 seconds to go up and back, what was the initial velocity of the throw to Kim? b) What was the initial velocity of the ball as seen by Joe? c) How high did the ball go to Kim? d) How high did the ball go to Joe? e) Sketch the path of the ball as seen by Joe roughly to scale.

**Newton's Second Law**

Newton's second law connects change of motion to force:

**Law II:** The change of motion is proportional to the net force acting on a body; and is made in the direction of the straight line in which the net force acts.

The way that a body moves depends on the **net force** acting on it, that is the combined action of all the forces acting on it. If an object moves at *constant velocity* there is *no net force* acting on it. If an object *speeds up*, then the net force on it is *in the direction of motion*. If an object *slows down*, the net force is *in the opposite direction* to the motion. If an object *changes direction*, the net force is *sideways* to the direction of motion. Newton added the idea that a net force is needed to change *the speed or the direction of motion* of an object or *both*

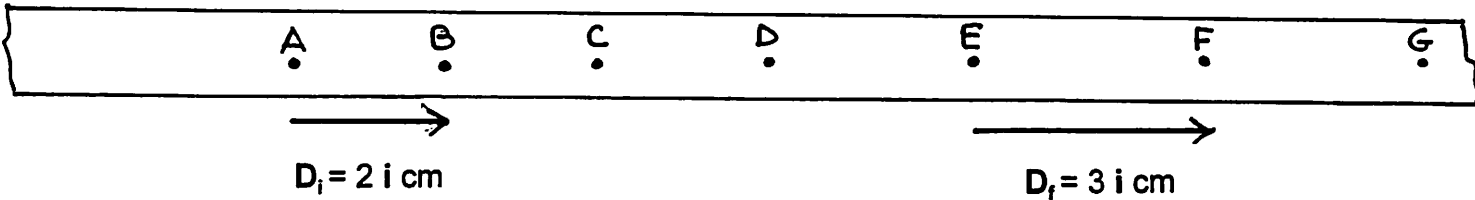
Newton's second law says that the change in velocity of an object is in the direction of the net force that acts on an object. If we can determine the direction of the change in velocity, we can determine the direction of the net force. We will look at a couple of

typical situations and analyse them from both the "commonsense" and Newtonian view.

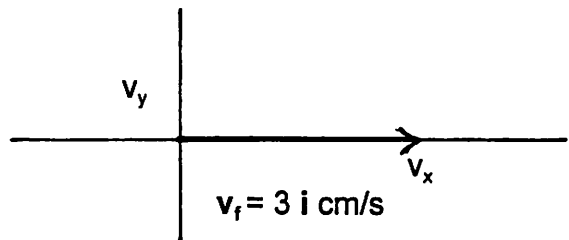
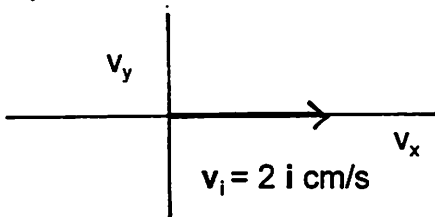
**Constant Force:** We will restrict ourselves to examples where a constant force is exerted on an object for a period of time. The picture below is the tape record of the motion of a glider across an air track. The position of the glider at successive times is given by the dots which were recorded at equal one second intervals by a spark-timer:

- from A to C, the equally spaced positions of the puck show that it has an initial constant velocity,  $v_i$ ;
- from C to E, a constant force,  $F$ , is applied to the puck;
- from E to G, the final velocity,  $v_f$ , is constant.

What is the direction of the force  $F$  that was applied?



The average velocity vectors have the same direction as the displacement vectors since average velocity in a time interval is given by displacement divided by the time. The glider moves from A to B in one second. From A to B,  $D_i = 2 \text{ i cm}$ , and the average velocity from A to B is,  $v_i = 2 \text{ i cm/s}$ . We can represent this velocity as an arrow of length 2 cm pointing in the +ve x direction. Similarly, the average velocity from F to G is,  $v_f = 3 \text{ i cm/s}$ .

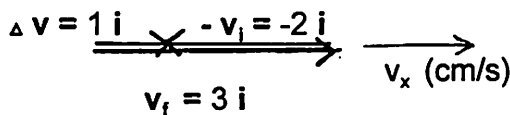


The "commonsense" model would predict that the force on the glider from C to E is in the direction of the motion.

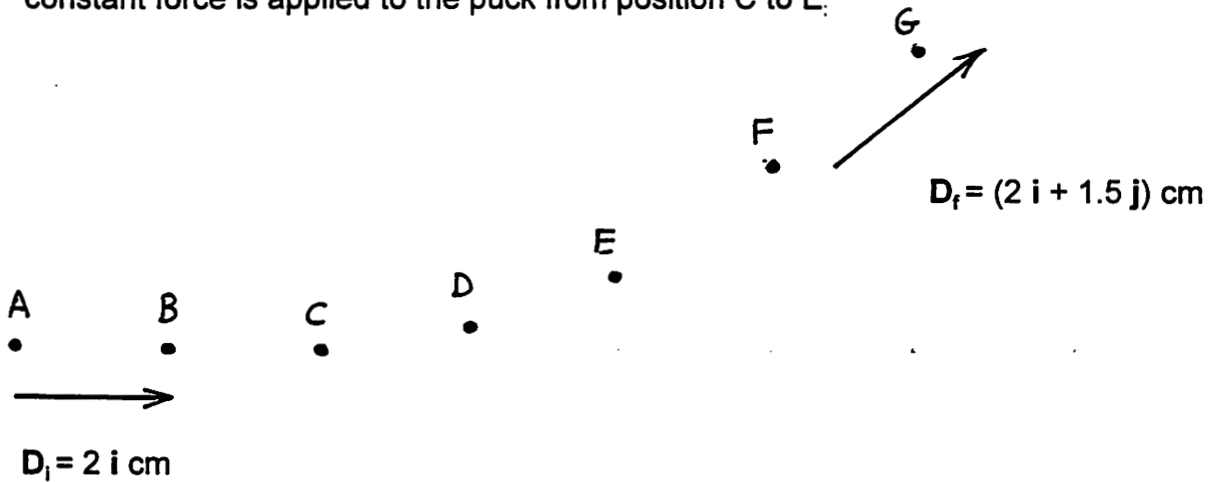


For the Newtonian prediction, we find the change in velocity,  $\Delta v$ , by subtracting the initial velocity,  $v_i$ , from the final velocity,  $v_f$ :  $\Delta v = v_f - v_i$ . Both the "commonsense" and the Newtonian model agree that the force is in the positive x direction:

$$\Delta v = v_f - v_i = (3 \text{ i} - 2 \text{ i}) \text{ cm/s} = 1 \text{ i cm/s}$$

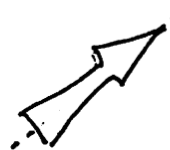


In the second example, a puck moves across an air table and the motion is given by the dots recorded on a sheet of paper by a sparker-timer at one second intervals. A constant force is applied to the puck from position C to E.

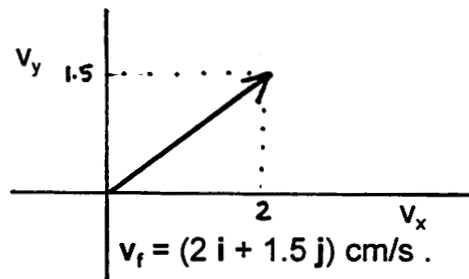
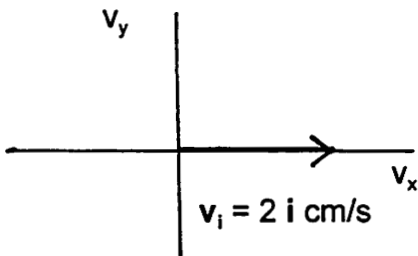


The "commonsense" model would predict that the force is in the direction of the final motion.

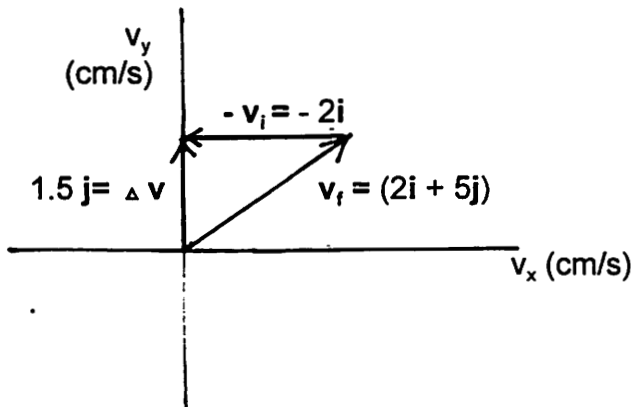
"commonsense" prediction  $F$



The initial velocity from A to B and the final velocity from F to G are found from the displacement vectors.



For the Newtonian prediction, we find the change in velocity,  $\Delta v$ , by subtracting the initial velocity,  $v_i$ , from the final velocity,  $v_f$ :  $\Delta v = v_f - v_i$ . The constant force,  $F$ , that was applied from C to E is in the direction of the change in velocity,  $\Delta v$ . In this case, the "commonsense" and the Newtonian model do not agree on the direction of the force.



$$\begin{aligned} \Delta v &= v_f - v_i = [(2 \mathbf{i} + 1.5 \mathbf{j}) - 2 \mathbf{i}] \text{ cm/s} \\ &= 1.5 \mathbf{j} \text{ cm/s} \end{aligned}$$

Newtonian prediction  $F$





## Question 5.

A puck is moving across a horizontal air table from top to bottom. Its motion is depicted by dots recorded at one second intervals by a sparkertimer.

• A

•

• B

•

• C

•

•

•

• D

a) Predict the direction of the force on the puck from B to C.

b) Draw a vector that represents the velocity from A to B.

c) Draw a vector that represents the velocity from C to D.

d) Use the vectors of b) and c) to find the change in velocity from B to C. Draw a vector that represents the direction of the force from B to C.

**Non Constant Force:** When a changing force is exerted on an object, then the change in velocity in a finite time interval only gives us the **average force** exerted on the object in the time interval. We must look at the change in the velocity vector during a very small time interval to find the instantaneous force at a particular time. We will not discuss the concept of instantaneous force.

## Summary

The "commonsense" model allows us to function in the world pretty well as long as we are dealing with objects at rest. It distinguishes between a state of rest and a state of motion.

The Newtonian model describes the motion of both objects at rest and objects that are moving. It distinguishes between a state of constant velocity (which includes zero) and a state of change of velocity (acceleration).

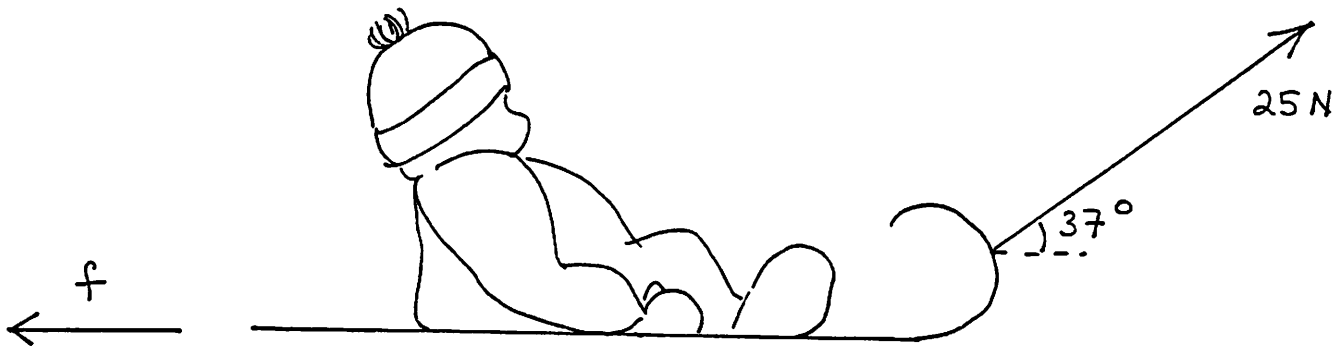
In the following table, we compare and contrast the predictions that may arise from using "commonsense" to those of the Newtonian model.

Physical State	Possible Prediction of "Commonsense" Model	Prediction of Newtonian Model	Agree?
An object is at rest.	There is no net force on it.	There is no net force on it.	YES
An object moves at constant speed.	There is a force acting on it.	If the object also moves in a straight line, there is no net force on it <b>but</b> if the object changes direction, there is a force acting on it.	NO
An object moves at constant velocity.	There is a force acting on it.	There is no net force on it.	NO
An object is released from a moving coordinate system.	The object does not retain the velocity of the coordinate system.	The object retains the velocity of the coordinate system.	NO
An object has no net force acting on it.	The object is at rest.	The object, is either at rest or moving at constant velocity.	NO
A force is exerted on an object at rest.	The object moves in the direction of the force.	The object moves in the direction of the force.	YES
A force is exerted on an object in the same direction as the object moves.	The object moves in the direction of the force.	The change in velocity is in the direction of the force. In this case, the object moves in the direction of the force.	YES
A force is exerted on a moving object.	The object moves in the direction of the force.	The change in velocity is in the direction of the force.	NO

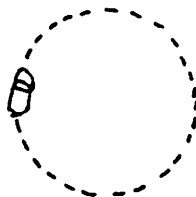
## Problems:

1. You are standing on a metro train wearing roller blades and not holding on to anything. a) Explain what happens to you when the train starts up using the Newtonian model. b) Explain what happens to you when the train stops using the Newtonian model.

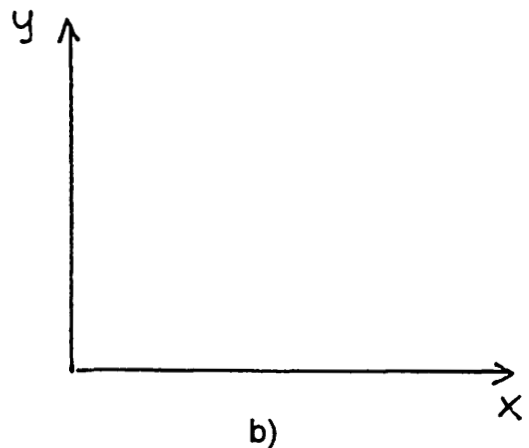
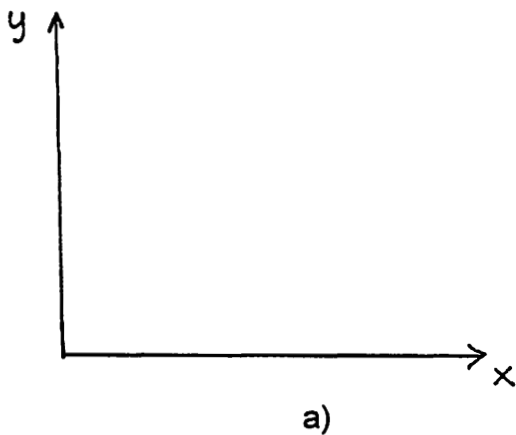
2. The child in the toboggan is being pulled along the snow at constant velocity as shown. What is the magnitude of the frictional force,  $f$ , acting on the toboggan? (Remember, the magnitude of any vector is a positive quantity.)



3. A racing car travels around a circular track at a constant speed of  $180\text{ km/hr}$ . Is there a force acting on the car? Explain your answer using the Newtonian model.



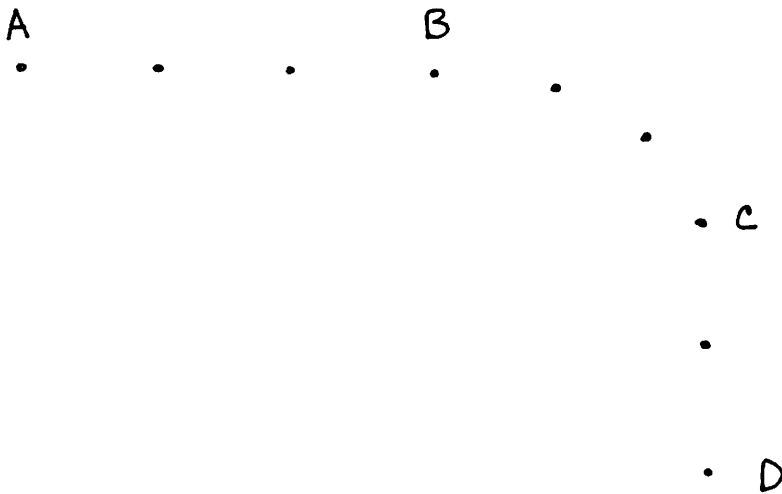
4. You are a passenger in a car and are not wearing your seat belt. Without changing its speed, the car makes a sharp left turn. Explain what happens to you using the Newtonian model.
5. Consider two people on opposite sides of a rotating merry-go-round. One of them slides a puck towards the other. Assuming that there is no friction, is the path of the ball straight with respect to the merry-go-round or straight with respect to the earth? Explain your answer using the Newtonian model.
6. A snowball is thrown straight up with a speed of 5 m/s from a snowmobile that is travelling at a constant speed of 10 m/s in a straight line. Using  $g = 10 \text{ N/kg}$  and ignoring air resistance, sketch the path of the snowball to scale from two points of view a) that of the driver and b) that of his friend who is watching from a snow bank.



7. A constant force acts on a puck and changes its velocity from  $\mathbf{v}_i = 3\mathbf{i} + 4\mathbf{j}$  to  $\mathbf{v}_f = -3\mathbf{i} - 4\mathbf{j}$ .
- Sketch the two velocity vectors as arrows on a  $v_y$ - $v_x$  coordinate system showing their magnitude and direction. Use the two arrows to find the change in velocity  $\Delta \mathbf{v} = \mathbf{v}_f - \mathbf{v}_i$ .
  - Use  $\mathbf{i}$ ,  $\mathbf{j}$  notation to find the change in velocity  $\Delta \mathbf{v} = \mathbf{v}_f - \mathbf{v}_i$ . Sketch  $\Delta \mathbf{v}$  on a  $v_y$ - $v_x$  coordinate system.
  - Check that you have the same answer for a. and b.
  - What is the direction of the force acting on the puck? Express your answer as an angle with respect to the x-axis.

8. A puck is moving across an air table from point A to point D. Its motion is depicted by the dots recorded at equal time intervals by a sparker-timer. Sketch an arrow to represent its initial velocity from A to B and an arrow to represent its final velocity from C to D. Take care that the length of the arrows that you use to represent the initial and final velocities are to scale (the easiest way to do this is to make the length of each arrow equal to the distance between two successive dots)

Use the two arrows to determine the change in velocity. What is the direction of the change of velocity and hence the direction of the constant force that was applied between points B and C?

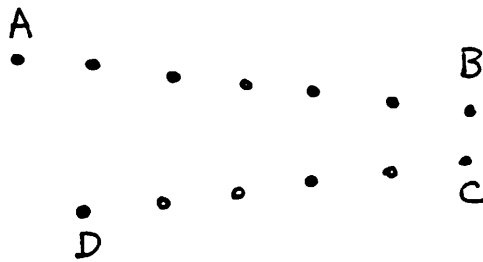


9. All the pictures below represent the motion of a puck on an air table where the dots are recorded at equal interval by a spark timer. In each case, the puck moves from point A to point D. The puck has an initial constant velocity from A to B as can be seen by the uniformly spaced dots in a straight line, then a constant force is exerted on it from point B to C so that its velocity changes. It has a final constant velocity from C to D. Find the direction of the change in velocity and hence the direction of the force required to change the motion of the puck. (Again take care that the length of the arrows that you use to represent the initial and final velocities are to scale, the easiest way to do this is to make the length of each arrow equal to the distance between two successive dots)

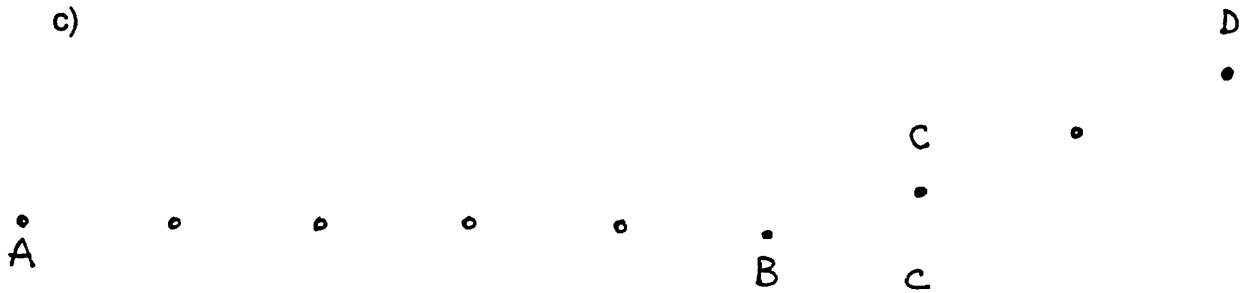
a)



b)



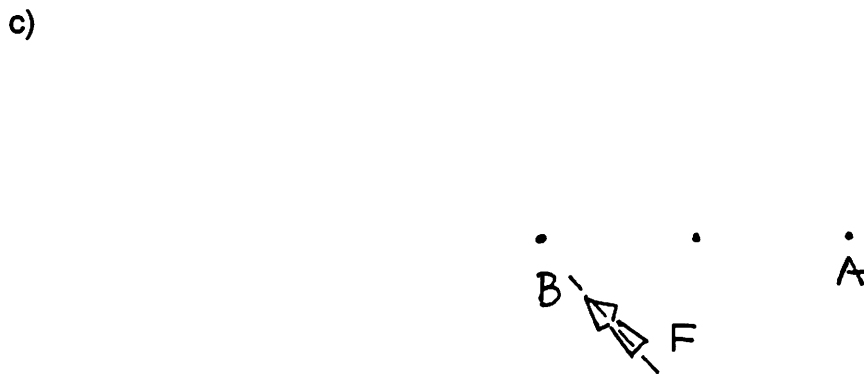
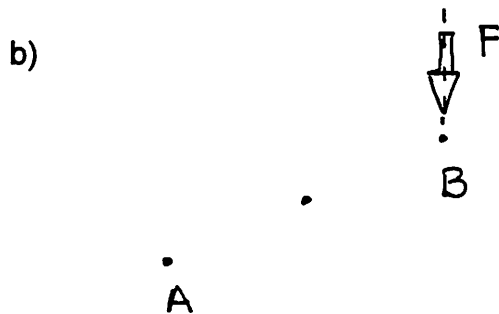
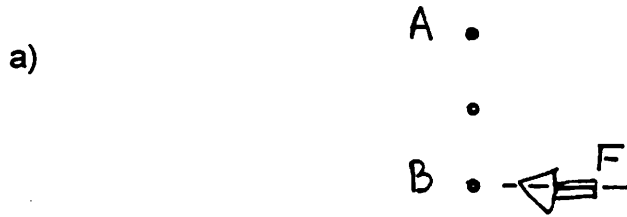
c)



d)

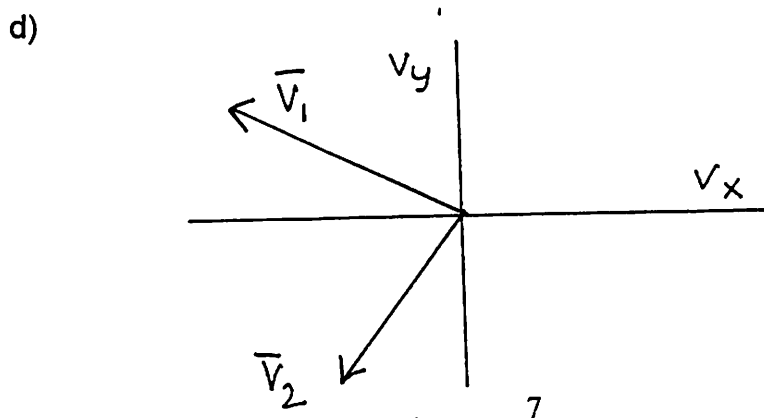
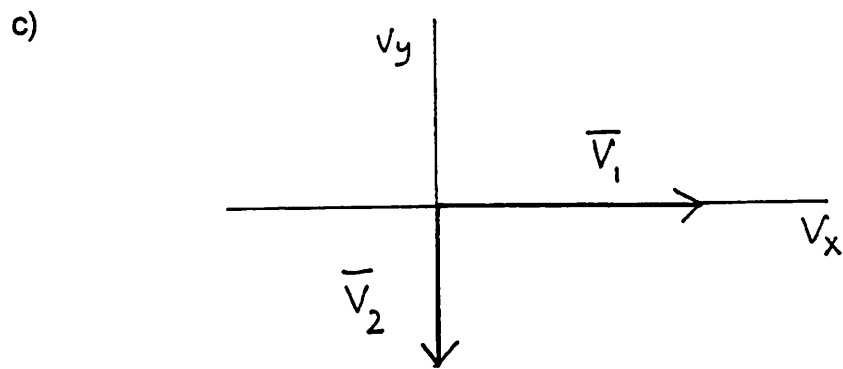
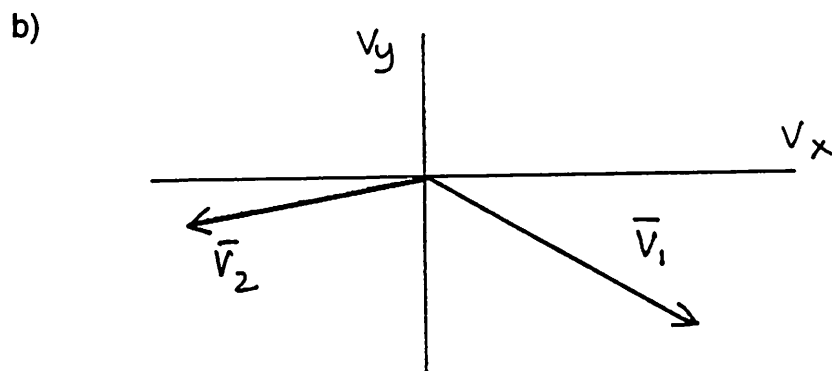
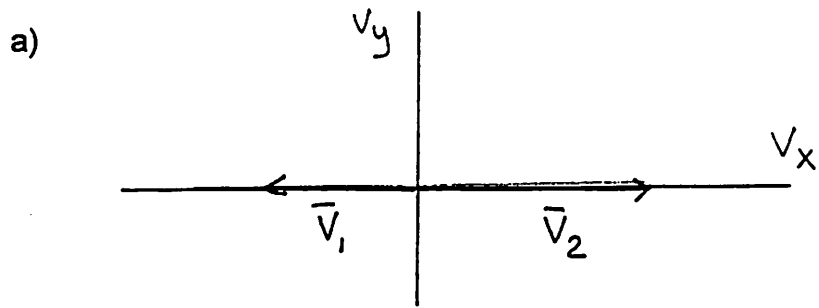


10. In each of the following cases, the puck is moving at constant velocity (i.e. constant speed in a straight line) from point A to point B when a constant force in the direction shown is exerted on it for a very short time at B. Complete the picture.





11. Each of the following diagrams shows the velocity vector,  $v_1$ , before a constant force was exerted and the velocity vector,  $v_2$ , after the force was exerted. Sketch the direction of the force showing your work to determine it.



## Appendix II

Notes distributed in the control class including  
the same set of problems as to the experimental class

Scattered throughout the text are questions. When you reach a question, answer it before you read further.

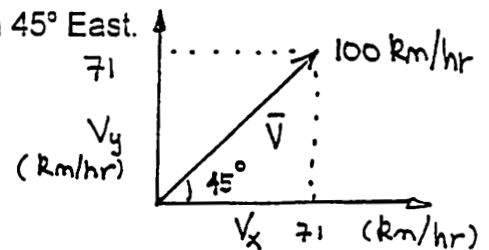
## Understanding Newtons First Two Laws

You are probably thinking "Not Newton's Laws again. I learned them in high school,  $F=ma$  and all that." Yes, you were introduced to Newton's Laws in high school, but you will be surprised to find that there is more to these laws than meets the eye. We believe that we can give you a deeper understanding of how these laws describe the physics of our world by looking at Newton's first two laws from a different point of view. We will not use  $F=ma$  or indeed any formulas!

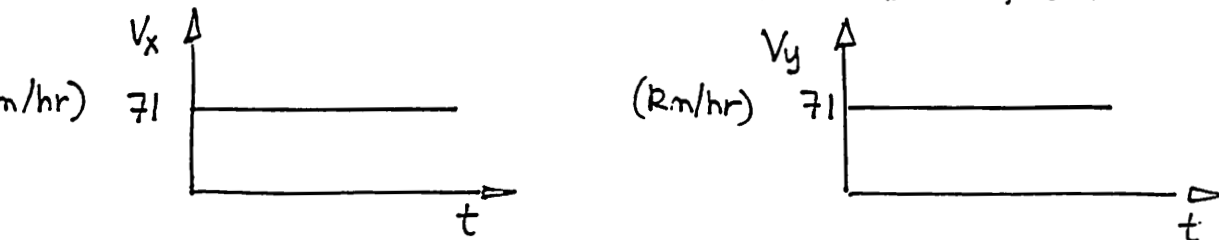
When presented with a physics problem, most first year students grab a formula, stick in the values and hope that the answer at the back of the book pops out. This process often fails. Our aim is to show that problem solving is more successful when students perceive the situation from a variety of perspectives: verbal, pictorial, and graphical.

For example, let's look at the motion of a car. We should be comfortable with any of the following ways of describing its velocity:

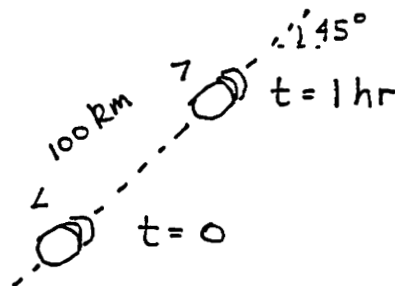
- 1) The car is driving at a constant velocity of 100 km/hr North 45° East.
- 2) The car has a constant velocity  $\mathbf{v} = (71\mathbf{i} + 71\mathbf{j})\text{km/hr}$ .



- 3) The motion of the car is shown graphically in the  $v_x$ - $t$  and  $v_y$ - $t$  graphs:



- 4) The motion of the car can be pictured by looking at its position at equal time intervals:



We may prefer one description over another in solving a particular problem but we need all these equivalent descriptions in our arsenal.

## Newton's First Law

Newton's first law of motion came from the work of Galileo who had the imagination to suggest that if an object is moving without anything touching or disturbing it, the object will go on forever coasting at uniform speed in a straight line. Galileo suggested that it is just as natural for a body to be moving in a straight line at a constant speed as to be at rest. He observed that if an object is given a push on a rough surface it will quickly come to rest but if a smooth object is given a push on a smooth surface, it will slide for much longer. He imagined an idealized situation where a perfectly smooth object is given a push on a perfectly smooth surface and slides forever. His genius was to make a model of a world without friction where an object once moving would only slow down if something disturbed it. This allowed him to think of friction as a retarding force.

Newton (circa A.D. 1700) took Galileo's work one step further with the idea that the only way to *change* motion is to use a force. Newton's first laws of motion restates Galileo premise:

**Law I:**        **A body continues in its state of rest or of constant speed in a straight line unless it is compelled to change that state by forces acting on it.**

*Watch out!*    *Consider the motion of a puck once it has left a hockey stick. Even when there is no longer a forward force acting on it, the puck keeps moving forward. It is only necessary to explain why it slows down and stops.*

You have learned that velocity describes both speed and direction. We can rephrase Newton's first law in terms of velocity: *A body will continue in a state of rest or constant velocity if there is no net force acting on it i.e. there will be no change in its speed or direction.*

*Watch out!*    *Note that there is a difference between constant speed and constant velocity. A car that rounds a corner at a constant 100 km/hr has constant speed but not constant velocity because the direction of its velocity is changing. A force is required for this change of direction.*

According to the first law, when we are pedalling a bike at a constant velocity (i.e. constant speed in a straight line), the force that propels the bike forward is equal and opposite to the force that retards it. There is no change in speed because the net force on the bike is zero. When we stop pedalling, the retarding force slows the bike down until it stops. Similarly when we have our car set on cruise control so that we are driving at 120 km/hr on a straight road, the net force on the car is zero. The force that propels the car forward is equal to the forces that retard it such as air resistance and friction. If we take our foot off the gas, the retarding forces eventually stop the car. In outer space,

there is no air resistance so no force would be required to keep a spaceship moving.

*Watch out! If you are given a physics problem where you are told that an object has a constant velocity, you are really being told that the net force on the object is zero! For example, if you are told that "for one section of the course, a downhill racer has a constant velocity of 80 km/hr", you are really being told that there is no net force on the skier.*

#### Question 1

It takes a force of 5 N to keep a book sliding on a table at a constant velocity. What is the frictional force acting on the book? (Do not continue until you have solved this question.)

Now let's look at what it means to be at rest or moving at a constant velocity. Usually, when we say an object is at rest, we mean with respect to the earth. It is amazing to think that even though we feel that we are at rest, the earth is whizzing through space. The earth has an average orbital speed of 30 km/s with respect to the Sun while the Sun has an average orbital speed of 200 km/s with respect to the centre of our Milky Way Galaxy. Alpha Centauri is moving away from us at 22 km/s but space aliens in Alpha Centauri would say that the Milky Way is receding at 22 km/s from them. Whenever we describe a velocity it is with respect to some **frame of reference**

A frame of reference that is moving at a constant velocity is called an inertial frame. . A train, moving at a constant 50 km/hr North with respect to the earth, is an inertial frame. If we are sitting in a soundproof, windowless room aboard such a train, we cannot tell the difference between the train at rest, the train moving at a constant velocity of 50 km/hr North, or the train moving at a constant velocity of 100 km/hr South. In fact, if we have no contact outside the room of the train, there is no experiment that we can perform that will enable us to determine the speed of the train. However, we can tell when the train starts as we feel the back of the seat pressing against us. We can also tell when the train speeds up, goes around a curve, slows down or stops, that is, we can tell when there is a change in velocity.

#### Question 2

- a) The train screeches to a stop. Use Newton's First Law to explain what happens to your body.
- b) The train goes around a curve counterclockwise. Use Newton's First Law to explain what happens to your body.

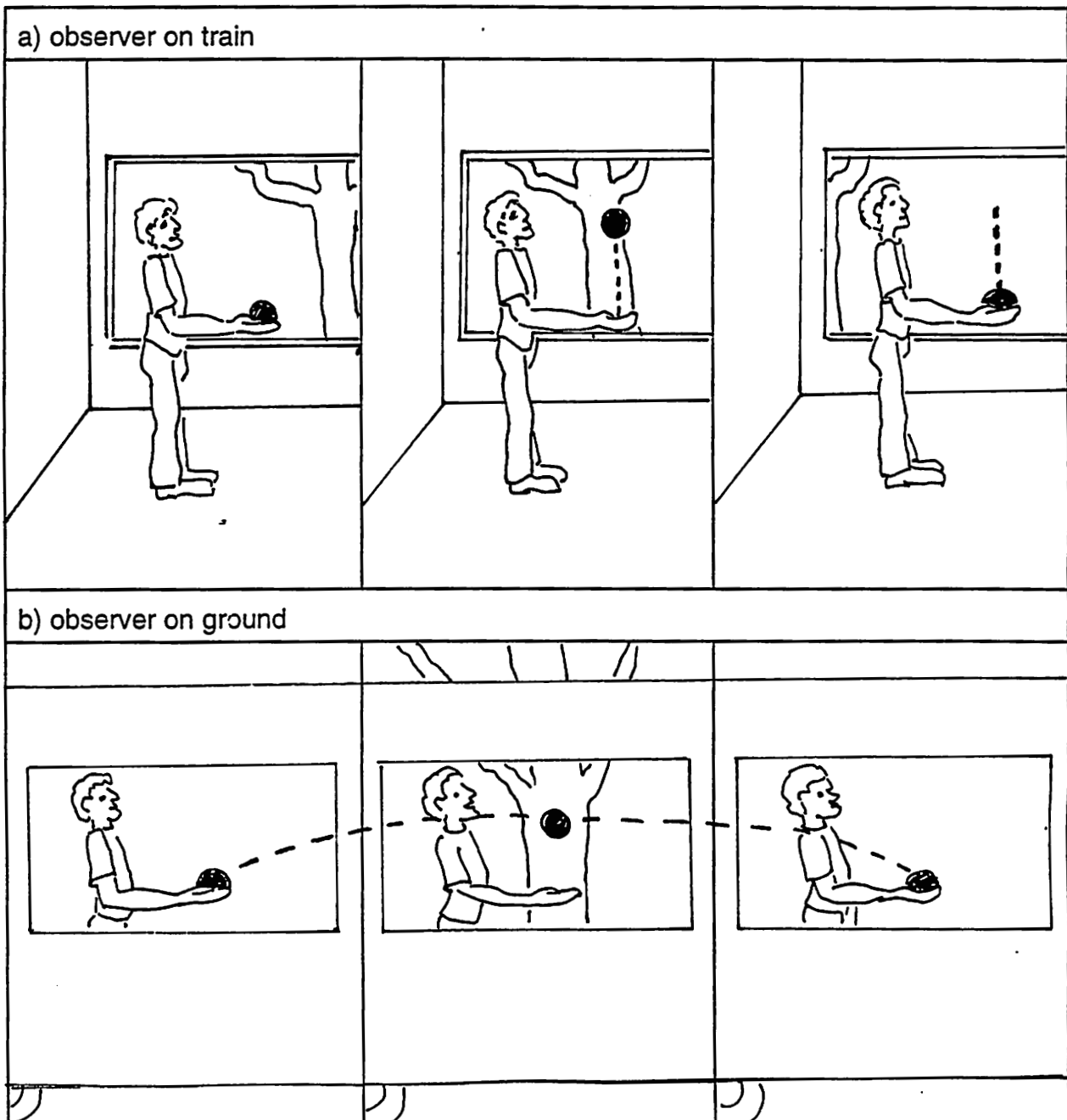
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its direction of motion. When the velocity changes, we are no longer in an inertial frame.

### Question 3

Suppose you are sitting in a soundproof, windowless room aboard a hovercraft. Which of the following can you detect from inside the room - a) horizontal acceleration, b) change of direction, c) speed of craft relative to ground, d) vertical acceleration, e) state of rest with respect to ground?

When you hold a magazine in your hand, the speed of the magazine can be given with respect to the plane or with respect to the ground. With respect to the plane, the speed of the magazine is zero, yet the speed of the magazine relative to the ground is 900 km/hr. Similarly if you are holding a ball on the flat car of a train travelling at 80 km/hr, the speed of the ball relative to you is zero but the speed of the ball with respect to the ground is 80 km/hr. If you throw the ball straight up in the air, to you the ball goes straight up and down while to an observer on the ground the path of the ball is a parabola.



Since the ball is at rest with respect to the train, it is travelling at the same horizontal speed as the train. The combination of its horizontal and vertical motions looks like a parabola to the person on the ground.

#### Question 4

Kim is sitting in a train playing with a toy ball. She is so absorbed in her game that she doesn't notice that the train is moving forward with speed 20 m/s, she thinks that the train is still stopped in the station. According to her, she's throwing the ball straight up and catching it in the same place. Joe is standing on the ground and he observes her game. a) If the ball takes a total of 1.5 seconds to go up and back, what was the initial velocity of the throw to Kim? b) What was the initial velocity of the ball as seen by Joe? c) How high did the ball go to Kim? d) How high did the ball go to Joe? e) Sketch the path of the ball as seen by Joe roughly to scale.

### Newton's Second Law

Newton's second law is based on the idea that the only way to *change* motion is to use a force.

**Law II:** The change of motion is proportional to the net force acting on a body; and is made in the direction of the straight line in which the net force acts.

The way that a body moves depends on the **net force** acting on it, that is the combined action of all the forces acting on it. If an object moves at *constant velocity* there is *no net force* acting on it. If an object *speeds up*, then the net force on it is *in the direction of motion*. If an object *slows down*, the net force is *in the opposite direction* to the motion. If an object *changes direction*, the net force is *sideways* to the direction of motion.

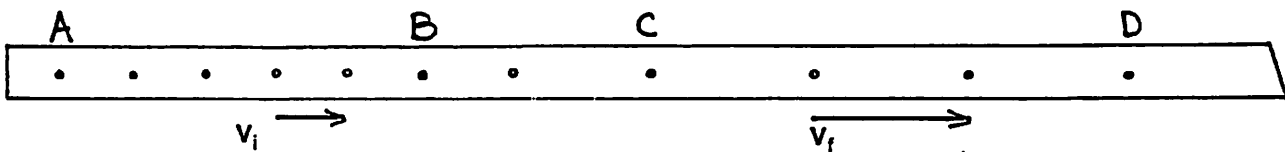
Newton added the idea that a net force is needed to change *the speed or the direction of motion* of an object or *both*.

Newton's second law says that the change in velocity of an object is in the direction of the net force that acts on an object. If we can determine the direction of the change in velocity, we can determine the direction of the net force.

**Constant Force:** We will restrict ourselves to examples where a constant force is exerted on an object for a period of time. The picture below is the tape record of the motion of a glider across an air track. The position of the glider at successive times is given by the dots which were recorded at equal time intervals by a spark timer:

- from A to B, the equally spaced positions of the puck show that it has an initial constant velocity,  $v_i$ ;
- from B to C, a constant force,  $F$ , is applied to the puck;
- from C to D, the final velocity,  $v_f$ , is constant.

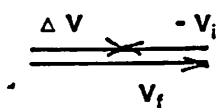
What is the direction of the force  $F$  that was applied?



#### Question 5

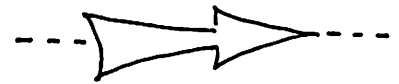
Guess the direction of the force acting from B to C in the motion above and sketch an arrow to represent this direction.

Using Newton's second law, we find the direction of the force by finding the direction of the change in velocity. The change in velocity,  $\Delta v$ , is found by subtracting the initial velocity vector,  $v_i$ , from the final velocity vector,  $v_f$ :  $\Delta v = v_f - v_i$ .

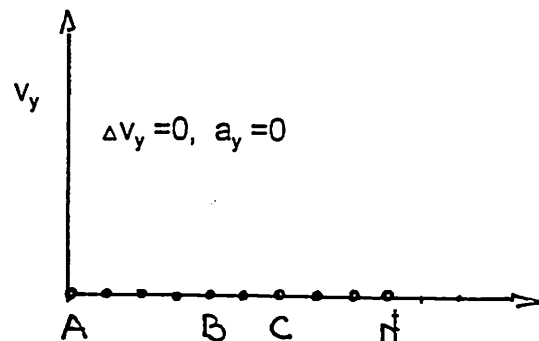
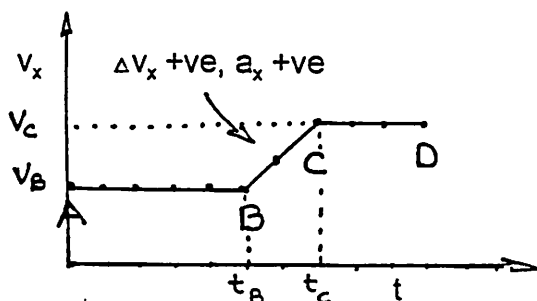


Direction of force

$F$



The motion can also be represented by graphing the components of velocity,  $v_x$  and  $v_y$ , versus time:



The change in velocity in the x-direction is positive from  $t_B$  to  $t_C$ . The slope is constant so



the acceleration in the x-direction is constant and given by:

$$a_x = \Delta v / \Delta t = (v_C - v_B) / (t_C - t_B)$$

There is no velocity in the y-direction, no change in velocity and no acceleration in the y-direction. Thus the acceleration vector is in the positive x-direction as is the change in velocity and the force. You are probably familiar with the equation  $F = ma$  which relates the net force vector to the acceleration vector. This equation is shorthand for the fact that the net force vector and acceleration vector are in the same direction and that the acceleration is proportional to the net force.

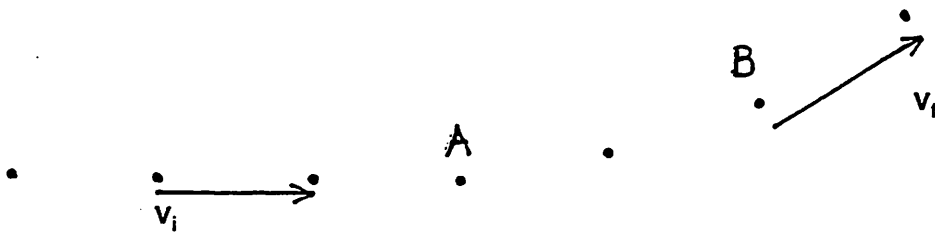
Question 6

The dots represent the motion of a puck moving from right to left across an air table. The dots were recorded at equal time intervals.



- a) Is there a net force on the puck from A to B?
- b) Draw a vector that represents the velocity from A to B.
- c) Is there a net force on the puck from C to D?
- d) Draw a vector that represents the velocity from C to D.
- e) Use the vectors of b) and d) to find the change in velocity from B to C. Draw a vector that represents the direction of the force from B to C.

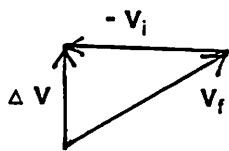
Here is an example of a 2-dimensional motion. A puck moves across an air table and its motion is given by the dots recorded on a sheet of paper by a spark timer. A constant force is applied to the puck from position A to B.



### Question 7

Guess the direction of the force acting from A to B in the motion above and sketch an arrow to represent this direction.

Using Newton's second law, we find the direction of the force by finding the direction of the change in velocity. The change in velocity,  $\Delta \mathbf{v}$ , is found by subtracting the initial velocity vector,  $\mathbf{v}_i$ , from the final velocity vector,  $\mathbf{v}_f$ :  $\Delta \mathbf{v} = \mathbf{v}_f - \mathbf{v}_i$ .

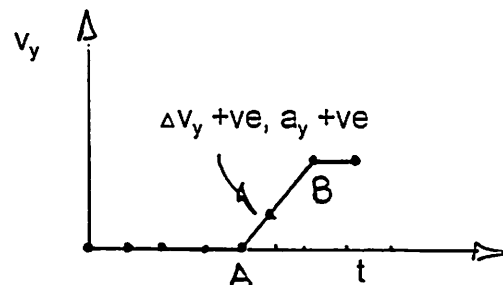
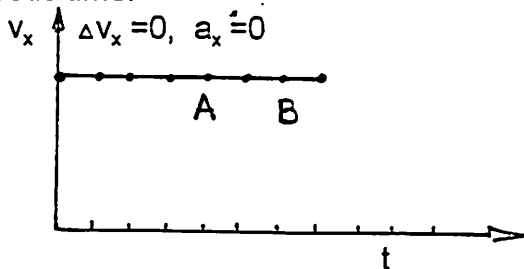


Direction of force

F



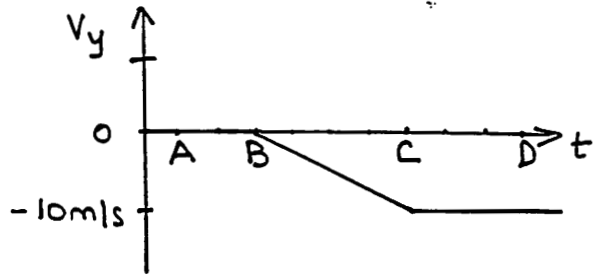
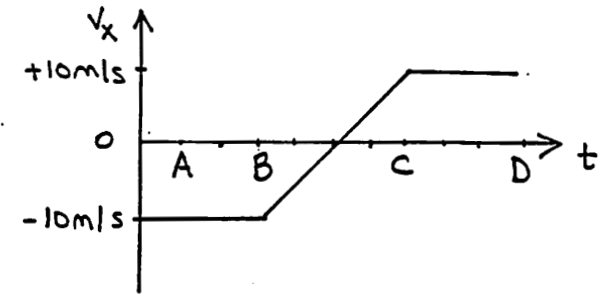
The motion can also be represented by graphing the components of velocity,  $v_x$  and  $v_y$ , versus time:



From A to B, the change in velocity and hence the acceleration in the x-direction is zero while the change in velocity and hence the acceleration in the y-direction is positive. The change in velocity, the acceleration and the force all point in the positive y-direction.

## Question 8

The  $v_x$ - $t$  and  $v_y$ - $t$  graphs for a motion are shown below.



- ) Is there a force acting between A and B?
- ) Sketch the velocity vector from A to B.
- ) Is there a force acting between C and D?
- ) Sketch the velocity vector from C to D.
- ) Sketch the change in velocity from B and C.
- ) Sketch the direction of the force acting between B to C.
- ) From the  $v_x$ - $t$  and  $v_y$ - $t$  graphs, find  $\Delta v_x$  and  $\Delta v_y$ . Use these components to sketch  $\Delta v$ .

## Question 9

A constant force acts on a puck and changes its velocity from  $\mathbf{v}_i = -2\mathbf{i} - 2\mathbf{j}$  to  $\mathbf{v}_f = 4\mathbf{i} - 4\mathbf{j}$ . Sketch the two velocity vectors. What is the direction of the force that must have acted on the puck? Express your answer as an angle with respect to the x-axis

**Non Constant Force:** When a changing force is exerted on an object, then the change in velocity in a finite time interval only gives us the **average force** exerted on the object in the time interval. We must look at the change in the velocity vector during a very small time interval to find the instantaneous force at a particular time. We will not discuss the concept of instantaneous force.

## Summary

Newton's First and Second Law describe motion and distinguish between a state of constant velocity (which includes zero) and a state of change of velocity (acceleration).

Physical State	Prediction of Newton's First and Second Laws
An object is at rest.	There is no net force on it.
An object moves at constant speed.	If the object also moves in a straight line, there is no net force on it <b>but</b> if the object changes direction, there is a force acting on it.
An object moves at constant velocity.	There is no net force on it.
An object is released from a moving frame.	The object retains the velocity of the frame.
An object has no net force acting on it.	The object, is either at rest or moving at constant velocity.
A force is exerted on an object at rest.	The object moves in the direction of the force.
A force is exerted on an object in the same direction as the object moves.	The change in velocity is in the direction of the force. In this case, the object moves in the direction of the force.
A force is exerted on a moving object.	The change in velocity is in the direction of the force.

### **Appendix III**

Sample of activities done by students in the experimental class

**Activity 2** *Work in pairs*

**Answer each question before you proceed to the next part of the activity.**

- a. *What can you say about the motion of a body if there is no net force acting on it?*

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- b. Look at a glider sitting on an air track at rest. *What is the net force acting on it?*

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- c. With the air turned off, give the glider a short push. *Why does the glider stop?*

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- d. Now turn on the air, but remove the cork from the air outlet at the end of the track so that only a small amount of air is coming through the holes. Push the glider again. Make a spark record of the motion before it hits the end of the track and label it as tape #1. *Why does the glider travel further than when the air was off?*

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- e. Draw a sketch of the glider, after you have stopped pushing it and before it stops, showing the direction it is moving. *Use an arrow to indicate the direction of the force that stops it.*

f. *Explain how the glider kept moving for a while after you stopped pushing it.*

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g. *Replace the cork in the air outlet so that all the air is coming through the holes. Push the glider again. Make a spark tape of the motion before the glider hits the end of the track and label it as tape #2. Why does the glider travel further than when only part of the air was coming through the holes?*

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h. *Under what conditions would the glider keep moving forever?*

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i. *Imagine that an object is launched in outer space at a constant speed in a straight line. Describe its subsequent motion if it doesn't bump into anything?*

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j. *Now what can you say about the motion of a body if there is no net force acting on it?*

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k. Compare your answers for questions a. and j.

l. Compare tapes #1 and #2. Explain what the dot records tells you about the motions.

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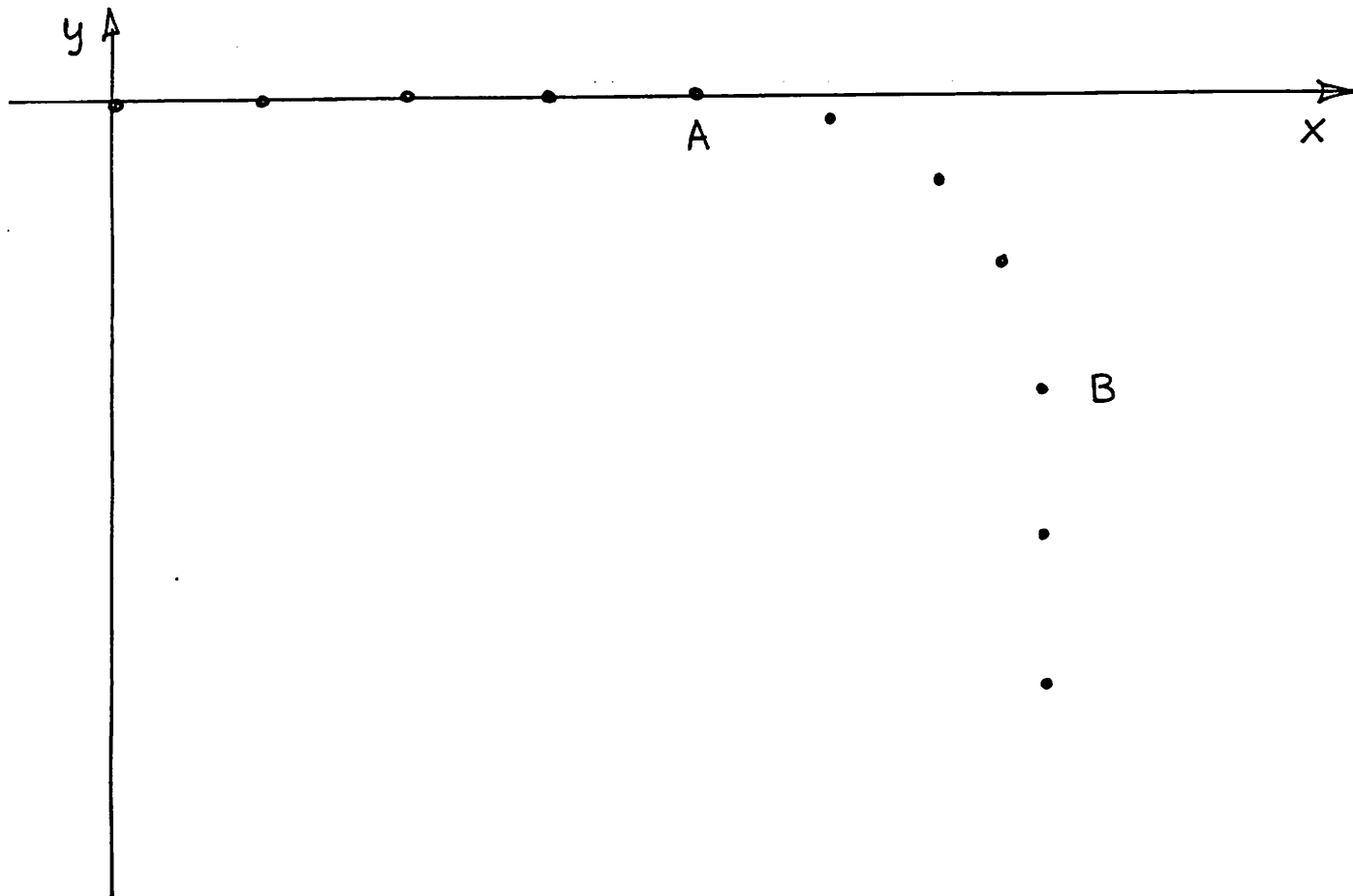
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**Activity 6** *Work on your own*

2-D Motion

- a. The motion of a puck across an air table is depicted by dots recorded at equal time intervals by a sparker-timer. In the case shown below, the puck moved from left to right across an air table with a constant force applied between points A and B. *Sketch an arrow to represent the direction of this force.*



- b. Use a ruler to draw a vertical line through each dot of the motion and place a dot where the line intersects the x-axis. The dots on the x-axis correspond to the x-motion of the puck. *Describe the x-motion in words.*

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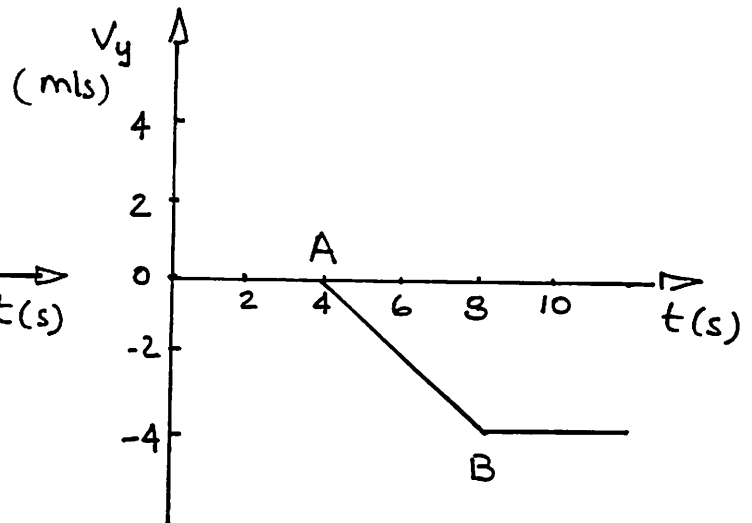
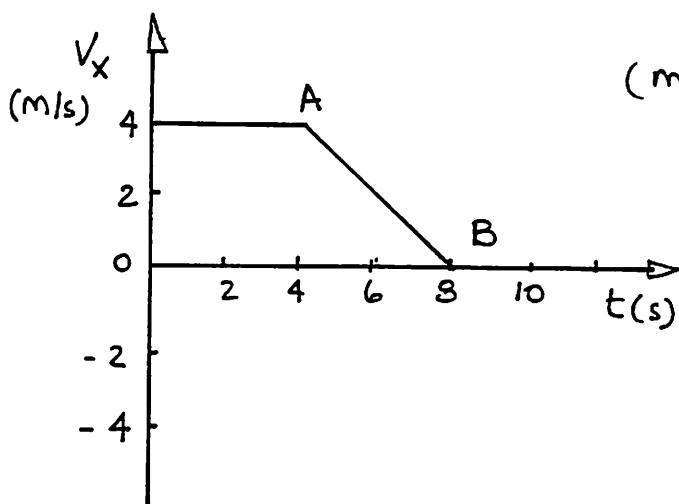
- c. Use a ruler to draw a horizontal line through each dot of the motion and place a dot where the line intersects the y-axis. The dots on the y-axis correspond to the y-motion of the puck. Describe the y-motion in words.

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- d. The graphs show the velocity in the x direction versus time,  $v_x-t$ , and the velocity in the y direction versus time,  $v_y-t$ . Calculate the change in velocity in the x direction from A to B,  $\Delta v_x$ , and the change in velocity in the y direction from A to B,  $\Delta v_y$ .



- e. Use the components  $\Delta v_x$  and  $\Delta v_y$  to sketch the vector,  $\Delta v$ . Show the direction of the force and compare it to your answer in a.

**Appendix IV**  
Questionnaire

## **Questionnaire on Classroom Activities**

1. Did you find the class stimulating?

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2. Did you have enough time to do the activities?

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3. Did the class give you a deeper understanding of Newton's first two laws?

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4. Was the pace of the class too slow, too fast, or just right?

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5. Do you have any suggestions that would improve the class?

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## Appendix V

Sample of consent forms used in this research program

# Changes in Student Knowledge Structures in Science

## Directions to the Student

A team of Science instructors at Vanier is doing research to help determine factors that affect student understanding and achievement in science and mathematics courses. Your instructor has agreed to allow this team to ask you some questions in aid of this effort. The team has prepared a questionnaire and would ask you to assist them by answering the questions in it. The questionnaire has been developed with the assistance of members of the Centre for the Study of Classroom Processes at Concordia University. All results of this questionnaire will be kept strictly confidential. This questionnaire, and your decision to assist in this effort (or not), will in no way influence your grade in this or any other course.

These questions were developed so that teachers and students might better understand how you and your classmates learn in science and mathematics courses. There are no correct or incorrect responses; this is about what you believe to be true. Note that we are interested in responses from both science and non-science students.

Please do not talk or share your answers with other students. Please answer the questions to the best of your ability. Again, remember that your answers will not affect your grades in any way. If you have any questions about how to answer, raise your hand. Do not shout questions out.

If you are interested in more information, or the results of this research, please contact Helena Dedic, principal investigator, at the Science Resource Centre, N301, 744-7016.

I, the undersigned, consent to participate with the assurance that the results will be kept confidential and that they in no way affect my grade in this or any other course. I understand that I have the right to refuse to participate at any time, and that such refusal will also in no way affect my grade in this or any other course. Further, should I decide to participate at this time, I can subsequently change my mind and any data that I have contributed will be withdrawn at my request.

PRINT NAME: \_\_\_\_\_

STUDENT #: \_\_\_\_\_

SIGNATURE: \_\_\_\_\_


**Appendix VI**  
**Motion Questionnaire**



# MOTION QUESTIONNAIRE

**USE A PENCIL TO RECORD ANSWERS ON THE OPSCAN SHEET.**

On the following pages there are a series of sentences labelled as 'statement "a"' or 'statement "b"'. Pairs of statements are arranged in a table below and your task is to decide which of the four possible links best fits the relationship between each pair: "a" tells you that "b"; "a" is consistent with "b"; "a" is not consistent with "b"; or "a" is unrelated to "b". For example, if "a" is " $X^2 = 25$ " and "b" is " $X = -5$ " then we would say that " $X^2 = 25$ " is consistent with " $X = -5$ ". Note that if the roles were reversed, that is "a" is " $X = -5$ " and "b" is " $X^2 = 25$ ", then we would say that " $X = -5$ " tells you that " $X^2 = 25$ ".

 **So, watch out: the order of the statements is important!**

Select the appropriate number 1 through 4 for each pair and record it on this sheet and the OPSCAN sheet. When you have completed the 8 questions below put your pencil down and wait for the instructor to collect your opscan sheet.

**PLEASE DO NOT TURN OVER THE SHEET UNTIL YOU ARE INSTRUCTED TO DO SO.**

- 1 "a" tells you that "b"
- 2 "a" is consistent with "b"
- 3 "a" is not consistent with "b"
- 4 "a" is unrelated to "b"

	statement "a"	$\Downarrow$	statement "b"
1	$X = 2$		$2X = 4$
2	$X = 2$		$Y = 5$
3	$X = 2$		$ X  = 2$
4	$X = 2$		$2X = 8$
5	$2X = 4$		$X = 2$
6	$Y = 5$		$X = 2$
7	$ X  = 2$		$X = 2$
8	$2X = 8$		$X = 2$

**IF YOU HAVE COMPLETED YOUR ANSWERS ABOVE AND ON THE OPSCAN PLEASE PUT YOUR PENCIL DOWN, AND WAIT FOR THE INSTRUCTOR TO COLLECT YOUR OPSCAN SHEET. DO NOT PROCEED FURTHER UNTIL INSTRUCTED TO DO SO.**

The first eight questions that you answered were intended to make sure that you understand the meaning of the four possible answers and the difference in meaning that can occur when a pair of phrases are reversed. In the table below the correct answers to the questions are presented and below that there is a short explanation for each answer. In particular please note the following:

- (i) when phrases "a" and "b" are reversed the answer may or may not be the same, as illustrated by questions 1 and 5 where they are the same, and 3 and 7 where they are not;
- (ii) the difference between "a" tells you that "b" and "a" is consistent with "b", as illustrated by questions 5 and 7;
- (iii) the difference between "a" is not consistent with "b" and "a" is unrelated to "b", as illustrated by questions 4 and 2.

- 1 "a" tells you that "b"
- 2 "a" is consistent with "b"
- 3 "a" is not consistent with "b"
- 4 "a" is unrelated to "b"

	statement "a"	$\Downarrow$	statement "b"
1	$X = 2$	1	$2X = 4$
2	$X = 2$	4	$Y = 5$
3	$X = 2$	1	$ X  = 2$
4	$X = 2$	3	$2X = 8$
5	$2X = 4$	2	$X = 2$
6	$Y = 5$	4	$X = 2$
7	$ X  = 2$	2	$X = 2$
8	$2X = 8$	3	$X = 2$

Please read the answers below and be sure that you have understood.

Consider the pair of statements # 1: " $X = 2$ " and " $2X = 4$ ". In this case we know that if  $X = 2$ , then by multiplying the equation by 2 we obtain the second equation  $2X = 4$ . Thus, we would score question #1 as 1 (tells you that).

Consider the pair of statements # 2: " $X = 2$ " and " $Y = 5$ ". We see no connection between X and Y so knowing that  $X = 2$  gives us no further information about the value of Y. Thus, we would score question #2 as 4 (is unrelated to).

Consider the pair of statements # 3: " $X = 2$ " and " $|X| = 2$ ". In this case we know that when we compute the absolute value of 2 we obtain 2. Thus, we would score question # 3 as 1 (tells you that).

Consider the pair of statements # 4: " $X = 2$ " and " $2X = 8$ ". In this case we know that if  $X = 2$ , multiplying the equation by 2 yields the equation  $2X = 4$ , so the equation  $2X = 8$  cannot be true. Thus, we score question # 4 as 4 (is unrelated to).

Consider the pair of statements # 5: " $2X = 4$ " and " $X = 2$ ". In this case we know that if  $2X = 4$ , then by dividing the equation by 2 we obtain the second equation  $X = 2$ . Thus, we would score question #5 as 1 (tells you that).

Consider the pair of statements # 6: " $Y = 5$ " and " $X = 2$ ". We see no connection between X and Y so knowing that  $Y = 5$  gives us no further information about the value of X. Thus, we would score question #6 as 4 (is unrelated to).

Consider the pair of statements # 7: " $|X| = 2$ " and " $X = 2$ ". In this case we know that if " $|X| = 2$ ", then X could be either -2 or 2. Since we are not sure which value is correct, we cannot chose "tells you that" and instead we would score question # 7 as 2 (is consistent with).

Consider the pair of statements # 8: " $2X = 8$ " and " $X = 2$ ". In this case we know that if  $2X = 8$ , dividing this equation by 2 yields the equation  $X = 4$ , so the equation  $X = 2$  cannot be true. Thus, we score question # 4 as 4 (is unrelated to).

**PLEASE DO NOT TURN THE PAGE.  
WAIT UNTIL THE INSTRUCTOR TELLS YOU TO START THE NEXT PORTION.**

In all of the following questions each statement, "a" or "b", refers to a car moving on a highway and describes observations of the motion made by a person standing on the side of the highway. Note that each statement represents a physically possible situation.

- |   |
|---|
| 1 "a" tells you that "b"<br>2 "a" is consistent with "b"<br>3 "a" is not consistent with "b"<br>4 "a" is unrelated to "b" |
|---|

	statement "a"	⇓	statement "b"
1	there is a net force due North acting on the car		the car is not moving
2	a ball dropped from the car falls along a parabolic path		there is a net force due North acting on the car
3	a ball dropped from the car falls straight down		the car has a change in velocity from 50 to 60 km/hr due North
4	the car has a change in velocity from 50 to 60 km/hr due North		there is no net force acting on the car
5	the car is moving at constant speed due North		there is a net force due North acting on the car
6	the car is not moving		there is no net force acting on the car
7	there is a net force due North acting on the car		a ball dropped from the car falls straight down
8	a moving car has a change of velocity due North		there is no net force acting on the car
9	there is no net force acting on the car		a ball dropped from the car falls straight down
10	a ball dropped from the car falls straight down		the car is moving at constant speed due North
11	there is a net force due North acting on the car		the car has a change in velocity from 50 to 60 km/hr due North
12	there is no net force acting on the car		a moving car has a change of velocity due North
13	there is no net force acting on the car		the car is moving at constant speed due North
14	there is a net force due North acting on the car		a moving car has a change of velocity due North
15	the car is not moving		there is a net force due North acting on the car

- 1 "a" tells you that "b"
- 2 "a" is consistent with "b"
- 3 "a" is not consistent with "b"
- 4 "a" is unrelated to "b"

	statement "a"	⇓	statement "b"
16	a moving car has a change of velocity due North		a ball dropped from the car falls along a parabolic path
17	the car is moving at constant speed due North		a moving car has a change of velocity due North
18	there is no net force acting on the car		the car is not moving
19	there is no net force acting on the car		the car has a change in velocity from 50 to 60 km/hr due North
20	a ball dropped from the car falls straight down		there is a net force due North acting on the car
21	there is no net force acting on the car		a ball dropped from the car falls along a parabolic path
22	a ball dropped from the car falls along a parabolic path		the car is moving at constant speed due North
23	the car has a change in velocity from 50 to 60 km/hr due North		a ball dropped from the car falls along a parabolic path
24	there is a net force due North acting on the car		the car is moving at constant speed due North
25	a ball dropped from the car falls straight down		there is no net force acting on the car
26	a ball dropped from the car falls along a parabolic path		the car is not moving
27	the car is moving at constant speed due North		a ball dropped from the car falls along a parabolic path
28	the car has a change in velocity from 50 to 60 km/hr due North		a ball dropped from the car falls straight down
29	a ball dropped from the car falls along a parabolic path		there is no net force acting on the car
30	the car is moving at constant speed due North		there is no net force acting on the car

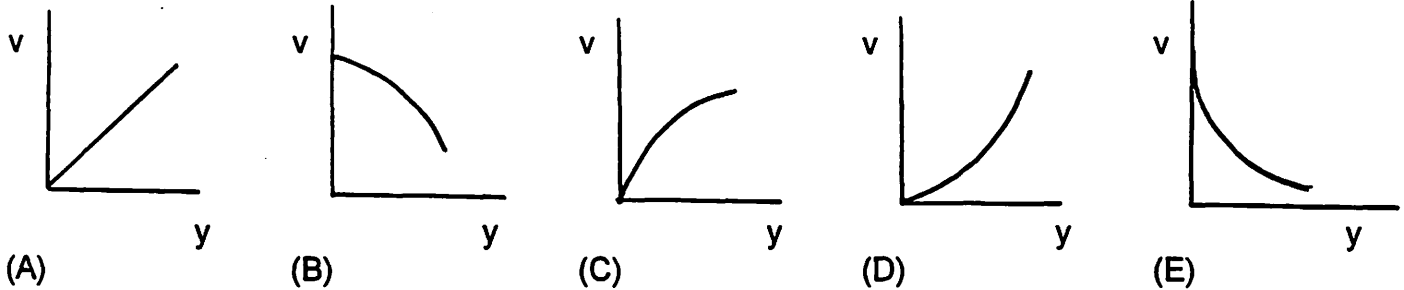
- 1 "a" tells you that "b"
- 2 "a" is consistent with "b"
- 3 "a" is not consistent with "b"
- 4 "a" is unrelated to "b"

	statement "a"	⇓	statement "b"
31	a ball dropped from the car falls straight down		the car is not moving
32	a moving car has a change of velocity due North		the car has a change in velocity from 50 to 60 km/hr due North
33	the car is not moving		a ball dropped from the car falls along a parabolic path
34	a ball dropped from the car falls along a parabolic path		the car has a change in velocity from 50 to 60 km/hr due North
35	the car is moving at constant speed due North		a ball dropped from the car falls straight down
36	the car has a change in velocity from 50 to 60 km/hr due North		there is a net force due North acting on the car
37	the car is not moving		a ball dropped from the car falls straight down
38	a moving car has a change of velocity due North		there is a net force due North acting on the car
39	there is a net force due North acting on the car		a ball dropped from the car falls along a parabolic path
40	a ball dropped from the car falls straight down		a moving car has a change of velocity due North
41	the car has a change in velocity from 50 to 60 km/hr due North		a moving car has a change of velocity due North
42	a moving car has a change of velocity due North		the car is moving at constant speed due North
43	a moving car has a change of velocity due North		a ball dropped from the car falls straight down
44	a ball dropped from the car falls along a parabolic path		a moving car has a change of velocity due North

**Appendix VII**  
Practice Problem Set

### Practice problems

1. An object is dropped from a high tower. Which sketch shows how the speed,  $v$ , varies with the distance fallen,  $y$ , when air resistance is ignored.



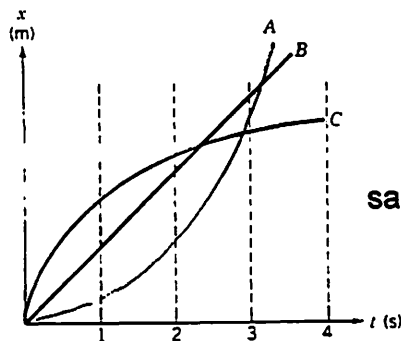
2. A body is fired upward with initial speed  $v_0$ . It takes time  $T$  to reach its maximum height  $H$ . Which statement is true?

- A) It takes half the time ( $T/2$ ) to reach half its maximum height ( $H/2$ ).  
 B) It takes half the time ( $T/2$ ) to decrease to half its initial speed ( $v_0/2$ ).  
 C) It has half the initial speed ( $v_0/2$ ) when it reaches half its maximum height ( $H/2$ ).  
 D) It has the same velocity just before it lands as when it was fired.

3. Two balls are dropped one after the other from a tall tower. After the second ball is dropped, which statement is true?

- A) The distance between the balls increases linearly with time.  
 B) The distance between the balls increases with the square of time.  
 C) The distance between the balls decreases linearly with time.  
 D) The distance between the balls decreases with the square of time.  
 E) The distance between the balls stays constant.

4. The  $x$  versus  $t$  graph depicts the journeys of three bodies, A, B and C. Which of the following statements are true?

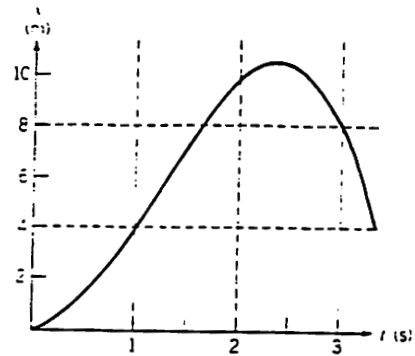


1. At 1 s, B has a greater velocity than A.
2. At 2 s, B has travelled the furthest.
3. When A meets C, A is moving faster than C.
4. At 2 s, A has the approximately the same velocity as B.
5. When A meets B, they have the same velocity.

- A) 1 only  
 B) 1 and 4  
 C) 1, 3 and 4  
 D) 1, 2 and 5  
 E) none of them

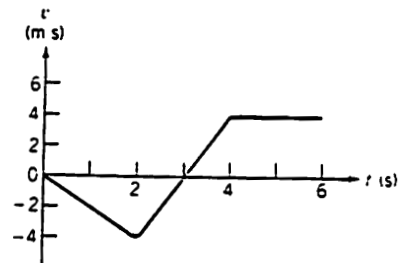
5. For the x-t graph, which statement is correct?

- A) From 0 to 3 s, the average velocity is 5 m/s.
- B) At 2.5 s, the instantaneous velocity is 10 m/s.
- C) At 1 s, the instantaneous velocity is 4 m/s.
- D) From 2 to 3 s, the average velocity is 2 m/s.
- E) From 1 to 3 s, the average velocity is 2 m/s.

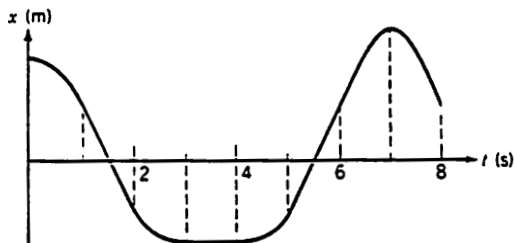


6. For the v-t graph, which statement is correct?

- A) The particle is slowing down at 1 s.
- B) The particle is not accelerating at 3 s.
- C) The particle has a negative acceleration from 2 to 3 s.
- D) The particle is slowing down at 2.5 s.
- E) The particle stops at 4 s.



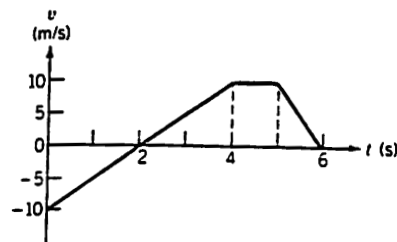
7. For the x versus t graph, which statements are correct?



1. At  $t = 3.5$  s,  $v = 0$  and  $a = 0$ .
2. At  $t = 7$  s,  $v = 0$  and  $a < 0$ .
3. At  $t = 5.5$  s,  $v > 0$  and  $a = 0$ .
4. At  $t = 1.5$  s,  $v < 0$  and  $a < 0$ .
5. At  $t = 7$  s,  $v = 0$  and  $a > 0$ .

- A) 1 and 3
- B) 2, 3 and 4
- C) 1, 2, and 3
- D) 3 and 4
- E) 3 and 5

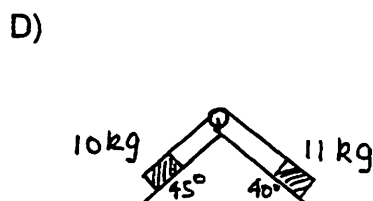
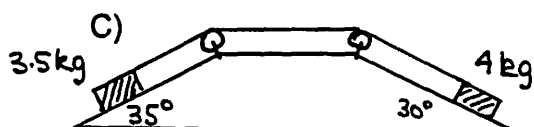
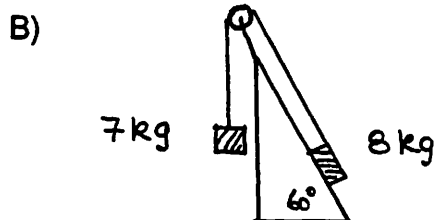
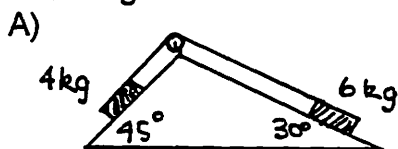
8. For the v-t graph, which statement is NOT true?



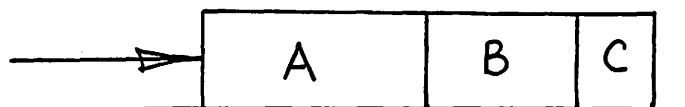
- A) The displacement for the first 4 s is 0 m.
- B) The instantaneous acceleration at 2 s is  $0 \text{ m/s}^2$ .
- C) The average velocity between 0 and 6 seconds is  $2.5 \text{ m/s}$ .
- D) The average acceleration from 2 to 5 s is  $3.3 \text{ m/s}^2$ .
- E) The acceleration at 4.5 s is  $0 \text{ m/s}^2$ .



9. A ball is thrown across a field. Assuming that air resistance is negligible, which statement is NOT correct?
- A) The horizontal velocity stays constant.  
 B) On the way up, the vertical velocity and acceleration are in opposite directions.  
 C) At the top the ball has no vertical velocity and no acceleration.  
 D) On the way down, the speed of the ball increases.  
 E) On the way down, the vertical velocity and acceleration are in the same direction.
10. A ball rolls off a horizontal table with initial speed  $v_0$  and lands on the floor in time  $T$ . Assume that air resistance is negligible. If the initial speed of the ball is doubled, which of the following statements is true?
- A) It takes half as long a time for the ball to land on the floor.  
 B) It takes the same time for the ball to land on the floor.  
 C) It takes less time for the ball to land on the floor, but not exactly half the time.  
 D) It takes exactly twice the time for the ball to land on the floor.
11. The horizontal distance that a projectile travels is called its range  $R$ . If a projectile is launched with initial velocity  $v$  at an angle  $\theta$  of less than  $45^\circ$  to the horizontal, which of the following statements is NOT correct? (Assume that air resistance is negligible)
- A) If  $\theta$  is increased to  $45^\circ$ , the range  $R$  increases.  
 B) If speed  $v$  is doubled, the range  $R$  is doubled.  
 C) If speed  $v$  is doubled, the range  $R$  is quadrupled.  
 D) If the horizontal component of the velocity is doubled, the range is twice as far.  
 E) If the vertical component of the velocity is doubled, the range is twice as far.
12. A girl, standing on a Metro train, throws a ball straight up. Which statement is NOT correct?
- A) If the train continues at constant velocity, the ball will land in her hand.  
 B) If the train accelerates when the ball is in flight, the ball will land behind her hand.  
 C) If the train speeds up when the ball is in flight, the ball will land in front of her hand.  
 D) If the train brakes when the ball is in flight, the ball will land in front of her hand.
13. If the blocks slide on the surfaces without friction, which system of blocks slides to the right?

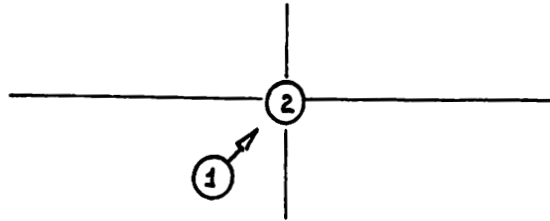


The following diagram is for both question 14 and 15. The mass of block C is three times the mass of block A while the mass of block B is twice the mass of block A. A force  $F$  pushes block A and the three blocks, A, B and C, slide at a constant acceleration.

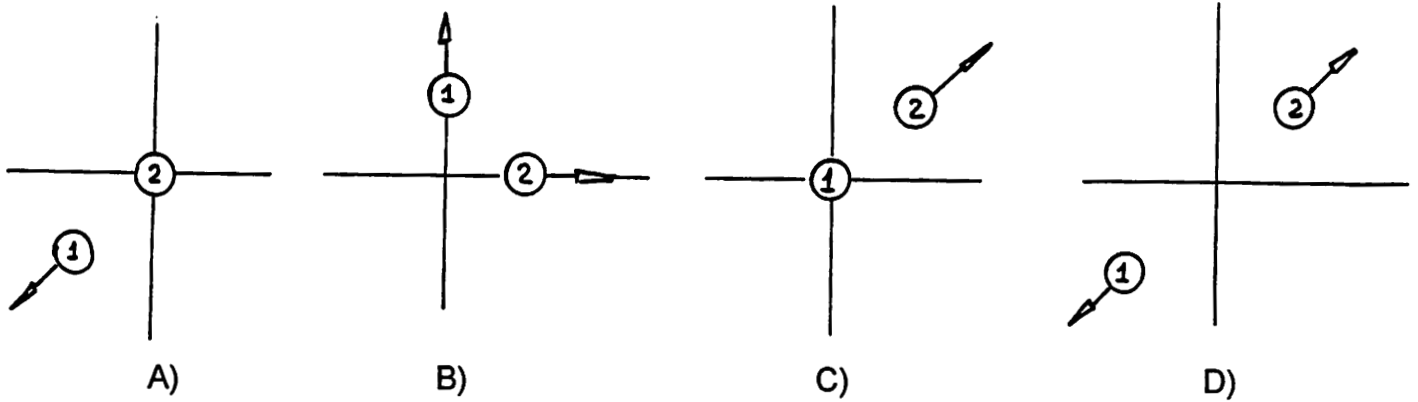


14. If there is no friction between the blocks and the surface in the above figure, which of the following statements is NOT true?
- A) A pushes on B with the same force that B pushes on A.
  - B) A pushes on B more than B pushes on A.
  - C) C pushes on B with less force than B pushes on A.
  - D) A pushes on B more than B pushes on C.
15. If there is friction between the blocks and the surface in the above figure, which of the following statements is NOT true?
- A) A pushes on B with the same force that B pushes on A.
  - B) A pushes on B more than B pushes on A.
  - C) C pushes on B with less force than B pushes on A.
  - D) A pushes on B more than B pushes on C.
16. In the spin cycle of a washing machine, the drum rotates and water flies out of the holes of the drum. Here are common explanations of the physics that is involved. Which one is correct?
- A) Centrifugal force causes the clothes to move to the walls of the drum.
  - B) A force acts away from the centre so the water is pushed straight out the holes of the drum.
  - C) The spinning action forces the water out of the holes leaving the clothes dry.
  - D) The drum exerts a normal force on the clothes to keep them inside.
  - E) The centrifugal force balances the centripetal force.
17. Claudia is riding a descending elevator which comes to a stop. Which of these statements describe her situation correctly?
- A) Since she is descending, she experiences a downward acceleration.
  - B) The normal force on Claudia is larger than her weight.
  - C) Her apparent weight is less than her weight.
  - D) There is a force that pushes her down into the floor so that she feels heavier.
  - E) The net force on her is equal to her weight.

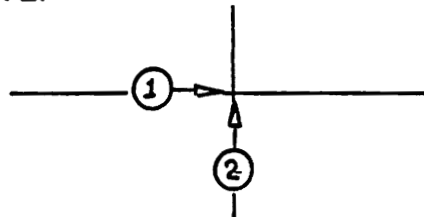
18. Two pucks of the same mass are on a frictionless surface. Puck 2 is at rest. Puck 1, moving in the direction of the arrow, has an elastic collision with 2.



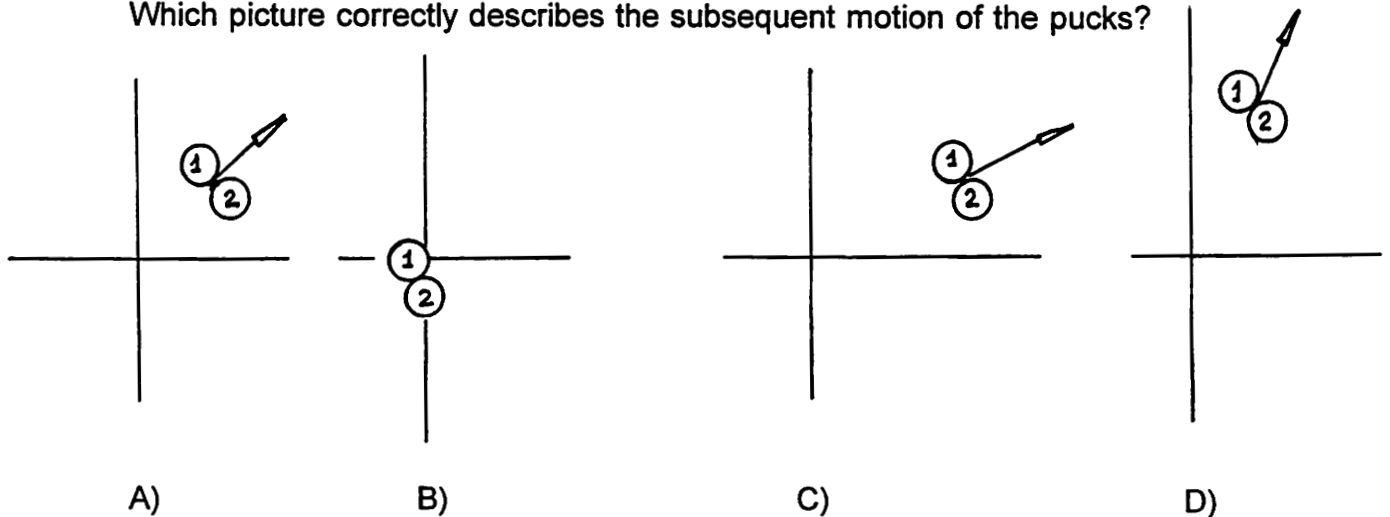
Which picture correctly describes the subsequent motion of the pucks?



19. Two pucks are moving towards each other on a frictionless surface. When they meet, they stick together. Both pucks have the same speed but puck 1 has twice the mass of puck 2.



Which picture correctly describes the subsequent motion of the pucks?



**Appendix VIII**  
Worksheet

Discussion:

1. An object is dropped from a helicopter flying at 50 m/s. The trace shows the movement of the object from the moment it was dropped.
  - a. Observe the trace on the screen in the first experiment and notice the vertical and horizontal displacements of the object. What do you conclude about the forces acting on the object?
  - b. Observe the trace on the screen in the second experiment and notice the vertical and horizontal displacements of the object. What do you conclude about the forces acting on the object?
  - c. Observe the trace on the screen in the third experiment and notice the vertical and horizontal displacements of the object. What do you conclude about the forces acting on the object?
  - d. Observe the trace on the screen in the fourth experiment and notice the vertical and horizontal displacements of the object. What do you conclude about the forces acting on the object?
2. Please, turn the tape recorder "ON". Discuss your conclusions with your partner and attempt to reach a consensus concerning what forces are acting on the object. Write down what you agreed upon:
3. With the tape recorder still on discuss and answer the following two questions:
  - a. How do you explain why the object moved as it did in each of these experiments?

- b. The forces show the observation of motion from whose perspective, the pilot of the helicopter or a bystander on the ground?
4. Turn the tape recorder "OFF". Let a third party join in our investigation, a bystander (represented by a box). He will watch the path of the object. Observe the traces on the screen in four experiments and notice how the vertical and horizontal displacements of the object change. Note the shape of the path in these four experiments. Write down your observations:

Experiment 1. Caption:

Experiment 2: Caption:

Experiment 3. Caption:

Experiment 4. Caption

5. What can you say about the forces acting on the object in each of these experiments?
6. Please, turn the tape recorder "ON" and debate with your partner what you learned about the motion of the object dropped from the helicopter: the path; the forces acting on the object; the importance of air resistance, the influence of the position of the observer on the trace of the path; and, how and when the path is a parabola as predicted by equations discussed in the previous class. Record your thoughts in writing below and on the back of this sheet.