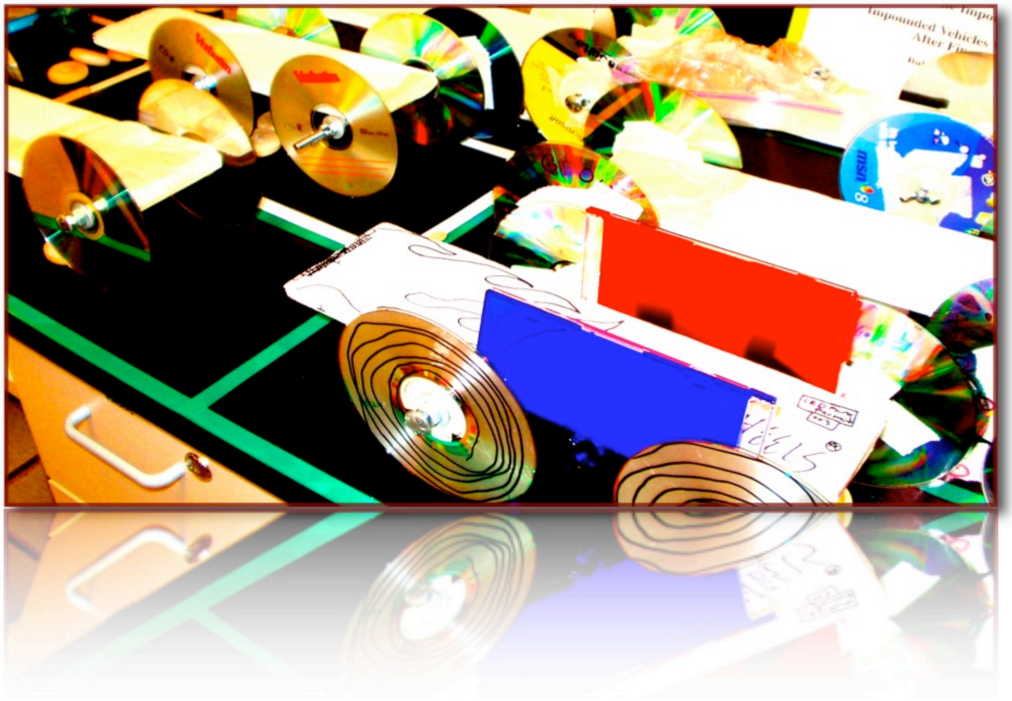
PROMOTING CONCEPTUAL CHANGE IN PHYSICS USING *models*



PAREA REPORT 2007 PA2005-010

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Promoting Conceptual Change in Physics Using Models

PAREA REPORT
September 2007

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PAREA project title: Promoting Conceptual Change in Physics Using Models

PAREA funding from: August 2005 – June 2007

Report submitted: September 2007-09-30

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Bibliothèque nationale du Québec

Bibliothèque nationale du Canada

ISBN number

ACKNOWLEDGEMENTS

We would like t thank the following individuals for their support and contribution of time and expertise towards the completion of this research project.

PAREA
Jeason Morin, Director of programs: PART, PAREA et PSCCC
Direction générale des affaires universitaires et collégiales
Ministère de l'Éducation, du Loisir et du Sport

Office of Professional Development & Research at Dawson College
Geoff Kloos
Suzanne Prevost

Office of Human Resources
Odette Dube

Administrative level support at Dawson College
Neville Gurudata, Academic Dean (former)
Robert Kavanagh, Academic Dean (present)
Raymond Bourgeois Dean of Science, Medical Studies & Engineering
Barbara Freedman, Dean of Instructional Development

Technical support:
Claude Jutras, Technician Physics
Norbert Kristof, Technician Physics
Jean-Claude Duval, Multi-media

Faculty support:
Joel Trudeau
Chris Roderick
Jonathon Sumner
Chris Whittaker
And, the other members of the
Physics Department

Research assistants:
Charles Stevens
Lauren Klimoff
Marilou Alforque
Kate Searle

Lastly, we would like to thank the thank the incredible group of students who participated in the case study research project 2006, as well as those who participated in the pilot study 2005. These hard working and dedicated young people are an inspiration to us all and are testament to the depth of learning that is possible at the college level.

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INTRODUCTION

Models are not 'right answers', rather, they are the methods and the products of science and it is quite impossible to teach and learn science without using models. How can we describe or explain atoms, genes, chemical reactions or continental drift without using one or more models? (Harrison and Treagust, 2000, p. 1013)

1.1 Overview

Scientists spend a great deal of time building, testing, comparing and revising models. In fact, models are the principle tools of modern science and they are integral to thinking and working scientifically (e.g., Brewer, 2001; Gilbert, 1993). For several decades the topic of models and model-based reasoning has been a focal issue of research in the philosophy of science (e.g., Nersessian & Hesse, 1963) and in the study of epistemology of models (Grosslight, Unger & Jay, 1991), but nowhere else does it have as much impact as in the study of science education. Science education researchers (Brewer, 2001; Buckley, 2000; Buckley, Gobert & Horwitz, 2006; Gobert, 2000; Harrison & Treagust, 2000; Hestenes, 1987; Reif, 1995; White & Frederiksen, 1998), educational practitioners and policy makers argue that the teaching of science should include model-based approaches (e.g. Quebec government high school science reforms; Natural Sciences and Engineering Research Council of Canada (NSERC); Centres for Research in Youth, Science Teaching and Learning (CRYSTAL) reports; U.S.A., National Research Council (NRC), 1996, 2000; in Europe, Eurydice, 2006; in Australia, Department of Education, Science and Training (DEST), 2005). In support of this proposition, Brewer's (2001) research suggests that scientific theories are more appropriately represented by model-based approaches, which should replace the formal mathematics-based instruction that is currently the norm. Furthermore, model-based theories are likely to be more intuitive for scientists and non-scientists, alike.

When scientific models are used as instructional tools, however, an important concern is how students come to understand and use them in the process of learning science, which raises several concerns. One issue is how learners, as individuals, may have difficulty learning to use scientific models for a variety of reasons including issues of conceptual misalignment between naïve understandings and the scientific model (i.e., conceptual change issues), as well as their possible naïve epistemology of scientific models and how that affects learning with models (e.g., Gobert & Discenna, 1997; Linn, Songer & Lewis, 1991).

Another issue is how learners mutually constitute the meanings of these scientific inscriptions and learn to use them as tools in the development of a deep understanding of causal mechanisms and structural features of scientific phenomena. From this perspective, models are cultural artefacts that mediate human action and knowledge construction. They are tools for communicating and negotiating understanding, reasoning and decision-making, and problem-solving and developing innovation.

But the causal mechanisms of scientific models cannot be observed directly (Clement, 2000). This necessitates the use of representations such as drawings, verbal analogies and other teaching models. For example, the solar system described in a 2D drawing, a 3D model with spheres and sticks, a computer model with moving parts, or compared to the atom with electrons moving around a nucleus. Such analogical or teaching models may themselves place considerable conceptual demands of their own on the learners (Harrison & Treagust, 2000). It is thus reasonable to suggest that there are both *affordances*[1] and constraints inherent in the different representations as they attempt to communicate the big historical ideas and discipline specific ways of doing things - e.g., 2D and 3D representations versus vectors and mathematical inscriptions.

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[1] When instructional designers design programs and activities they do so with the intention of building in opportunities for actions that lead to learning. Such opportunities are considered affordances of the instruction, or affordances for learning. The term affordance was coined by psychologist James Gibson (1966) and grew out of his work with visual perception – i.e., The Ecological Approach to Visual Perception (1979). Affordance, thus, describes the possibility of action "that is latent within the environment." For instance, both a chair and a bar stool hold in common the possibility of providing seating for the average adult, but not so for the average toddler. In the case of the latter, she does not have certain prerequisite capabilities, such as balance, to be able to use the affordances of the bar stool. In the case of instruction, this is all too common a problem. The textbook used in a physics course has the possibility of informing learners about Newton's laws, but not so if the learner cannot read or comprehend the language or the concepts held within. Or, the learner cannot take necessary actions to determine the explanatory goals of these laws and construct the necessary relationships between real world phenomena and the abstract models. So there is something more than mere affordance, there is "the ability to perceive affordances" (Norman, 1988). Thus there are dependences between the capabilities of the learner and the designed affordances of instruction. Such dependences include their goals, plans, values, beliefs and interests.

These differences may differentially implicate how understanding and use of models is mutually constituted, depending on the learners' prior knowledge and capabilities. Using models can require sustained cognitive effort and ability to identify structural elements of a phenomenon or process, what we will refer to as "deep" learning. Students generally need support to accomplish this level of reasoning (Clement, 2000). To make matters worse, students often learn and use scientific models in an algorithmic manner, rather than a relational manner (Reif, 1995). They also view individual models to be complete and, not merely partial, explanations or points of view (Harrison & Treagust, 2000).

In this research we were concerned with how first year science students come to construct, understand and use models in the process of learning physics. We were also interested in finding out the affordances and constraints of different representations commonly used to teach scientific models. And, lastly, we wanted to understand what types of dependencies might exist between the uptake of affordances and the learners' cognitive capabilities and social circumstances of collaborative engagement. Our research questions are described below.

1.2 Research Questions

In Volume I we address the following research questions:

1. How does a model-centered intervention, designed to have certain affordances, influence students' learning of physics concepts?
    a. What cognitive, social and cultural factors influence whether these affordances are recognized and acted on?
    b. How are the intervention's scaffolding tools used – i.e., model-bridging tools? Can these tools mediate learning in this context (collaborative groups)?
2. Does this explicit reasoning with and about models influence students' understanding of models as an epistemic form?
3. What are the implications of using this intervention in a collaborative group context?

And drawing on these findings, we will attempt to make recommendations that may be of use to physics teachers, the science sector, and science education, in general?

In Volume II we will answer the following questions:

4. How does the larger population of first year science students compare to our sample of participants on the same assessment measures (i.e., the FCI, ARLIN test of Formal Reasoning, Nelson Denny, and so on)?
5. What correlations are there between the FCI and other important factors at play for first year Cégep students?
6. What recommendations can we draw from our findings that may be of use to physics teachers and FCI researchers?

THEORETICAL BACKGROUND

2.1 Learning and Instruction

Starting with the big picture of learning and instruction, socio-cognitive and situated theories of learning tell us that learning is primarily a social process (e.g., Greeno, 1998; Lave & Wenger, 1991; Vygotsky, 1978). Vygotsky suggests that learning is the internalization of social interactions that are culturally mediated. From this perspective, learning can be characterized as changes in participation and use of representational systems such as conceptual models that represent phenomenon and other cultural tools that come to have very specific meanings in their respective disciplines. But there is more, Roschelle and Clancey (1992) argue that the goal of learning is not to just make experience meaningful in a personal way but to become a member of a community (à la Lave & Wenger, 1989). They propose that to accomplish this goal requires "simultaneous, coordinated changes to one's ways of seeing, talking and acting" (p. 438). In collaborative tasks one student's social actions can orient the other's perceptual processes, which can bring students' explanations closer to looking and sounding like the qualitative description of full participants, i.e., experts.

Such theories also posit that authentic tasks, and contexts, afford the types of participation and discourse that promotes learning (e.g., Rogoff, 1990). In the effort to solve authentic problems in context, learners have opportunities to participate and articulate personal understanding and negotiate meaning (i.e., they do certain types of *work*, both social and cognitive, in their interactions and discourse). This is accomplished through the construction of *joint problem space* (JPS; Roschelle & Teasley, 1995), what has been generally referred to as *common ground* (Clark & Schaefer, 1989; Stalnaker, 1978); which, we will later show may also be referred to in terms of types of shared mental models, e.g., a *consensus model*. But first, we distinguish between the notions of joint problem space and the notion of common ground.

Joint problem spaces support problem-solving activity by integrating semantic interpretations of goals, features, operators and methods. Roschelle and Teasley (1995) propose that participation in the creation and maintenance of the joint problem space is the fundamental activity in collaborative problem solving. Common ground, refers to the prior beliefs, assumptions and other information people bring with them as mutually shared background to the conversation – common knowledge and taken for granted ways of acting. When we talk about common ground, we make three assumptions: (1) common ground (or mutual knowledge) are the presuppositions about what is known or not known; (2) common ground can be added to, systematic *accumulation of common ground* (Clark & Schaefer, 1998); and (3) common ground is revealed in the unilateral action, the rule and norm-based action and reciprocal actions taken by individuals to engage in discourse; what we discuss as *contributions to discourse* (Clark & Schaefer, 1998). Such contributions, and their uptake or rejections, further help to show what is valued by others, what they believe to be true or not true, what norms they govern their actions by, and so on (e.g., Cobb, 2002).

In addition to those socio-cultural mechanisms of communication and sense-making, social practices and learning is influenced by disposition, agency and identity (e.g., Holland, Skinner, Lachicotte & Cain, 1998; Lave & Wenger, 1991; Nasir, 2002). Learners display a sense of agency when they accept or take the authority to become active participants and contributors to their own knowledge construction (e.g., Charles & Kolodner, submitted). The development of agency is complicated by socio-cultural and psychosocial phenomena, such as the individual's knowledge of and ability to use and creatively transform social structures, i.e., rules, norms, practices (Sewell, 1992); as well as notions of identity in social practice, e.g., *positional identity* (Boeler & Greeno, 2000; Holland, et al., 1998).

Positional identity is our sense of identity based upon how others position us socially. Greeno (2005) suggests there are two kinds of positioning: systemic and semantic. The former refers to the degree of authority given to initiate contributions, question or challenge the proposals of others, and provide or demand satisfactory explanations relating to the available resources. The latter refers to degree of acceptance given to one's contributions to making meaning and judging appropriateness of methods and interpretations – consistent with the notion of "conceptual agency" (Pickering, 1995). We believe that these three aspects of self within society and culture influences how students take on tasks in collaborative activity as well as how they take up designed affordances for learning. In short, these notions, along with the student's individual cognitive capabilities, may well have equally important roles in learning.

But how does this all come together with our instruction, learning with models? We turn next to this discussion and start first by describing what are models and why they are critical in science education.

2.2 Models and Modeling

The form taken by a model depends on its purpose and how it is to be used. A model can be concrete, abstract or theoretical as long as it facilitates investigation, understanding and communication. Generally speaking, a model is a simplified, runnable system that represents some 'target' process or interaction (Ingham & Gilbert, 1991; White & Frederiksen, 1990). It concentrates attention on specific aspects of the system and identifies certain things as important variables to be examined and tested. It consists of sets of rules and representations that provide temporal and spatial bridges that allow us to slow down or speed up time and/or take global or local perspectives thus enabling us to predict and explain phenomena. In short, it enables aspects of the system, i.e., objects, events, or ideas which are either complex, or on a different scale to that which is normally perceived, or abstract, to be rendered either visible or more readily visible (Gilbert, 1995).

A model may be reified, represented, in different types of media, including computer simulations, static drawings, mathematical equations, and words. When it comes to learning, it is commonly believed that the learner constructs some internal representations (mental models) of the teaching or instructional model, ideally, these representations share critical features and find overlap in the common ground, described earlier.

Running a model allows one to collect data, which in turn can test the theory the model represents. Models as representations sometimes add complexity, structure, and a level of explanation that is not inherent in the phenomena itself being described (Gobert & Buckley, 2000). Mechanisms within the models can be used to explain a variety of phenomena. They can be intuitive causal mechanisms, such as pushing or pulling; or, equilibrium mechanism such as moving from high to low concentrations. Links among models are created through simple "transformations" of the mechanisms and representations used in the models (Lakoff, 1987).

2.2.1 Model Typologies

Harrison and Treagust (2000) categorize analogical models into ten typologies: (1) scale models, (2) pedagogical analogical models, (3) iconic and symbolic models, (4) mathematical models, (5) theoretical models, (6) maps, diagrams and tables, (7) concept-process models, (8) simulations, (9) mental models, and (10) synthetic models. They further categorize these ten into groupings that describe their general characteristics (items 1 and 2), their purpose (items 3-5 – building conceptual knowledge), their representational form and function (items 6-8 – depicting multiple concepts and/or processes) and their ontological and epistemic considerations (items 9-10). Table 1 attempts to catalogue these model types.

Table 1. Catalogue of model types.

Characterization	Typology Harrison and Treagust (2000)	Gilbert (2004) Ontological & epistemic considerations	Modes of models Gilbert (2004)
General characteristic	Scale models		Concrete Mode
	Pedagogical models	Hybrid models; Teaching models; Consensus Models; Expressed Models	Verbal Mode; Gestural Mode
Purpose of models	Iconic & symbolic models		Symbolic Mode
	Mathematical models		Symbolic Mode
	Theoretical models	Historical models	Symbolic Mode
Representational form & function	Maps, diagrams & tables		Visual Mode
	Concept-process models		Verbal Mode
	Simulations		Visual Mode
Ontological & epistemic considerations	Mental	Consensus Models; Expressed Models	Verbal Mode; Gestural Mode
	Synthetic		Gestural Mode; Verbal Mode;

General characteristics of models: *scale models* are simple toy-like representations reflecting scaled down or scaled up versions of things and do not attempt to describe the internal structure, function or use of the things they represent (Black, 1962, cited in Harrison & Treagust, 2000). *Pedagogical analogical models*, on the other hand, include all the analogical models used in teaching and learning. Gilbert (2004) refers to these as *teaching models*, and sometimes the mixing of such models to create *hybrid models*, that are designed to support learning. These models share information with the target phenomenon or thing and are designed to promote these correspondences with the unobservable, as such, they tend to be oversimplifications or exaggerations. For example, models of the human heart as a simplified drawing, or a model of a molecule as a solid balls joined by sticks.

Purpose of models. *Iconic and symbolic models* are used to present formulas and equations. Such models, though embedded into the language of science, are not reality but need to be interpreted, e.g., CO_2 represents O=C=O. *Mathematical models* such as mathematical equations and graphs are used to express and depict conceptual relationships, e.g., F=ma; Boyle's Law. These models are perhaps the most abstract forms used, and also the more closely representative of the phenomenon or thing (Kline, 1985). Harrison and Treagust (2000) are quick to point out that such models are also represent ideal states, and not reality. Citing Hewitt (1987), they also infer that these models require certain mediating representations such as verbal qualitative explanations. *Theoretical models* describe well-grounded and tested theories. For example, Newton's laws, which explains the motion of objects, how velocity changes and where forces come from; the kinetic theory, which explains the expansion of gases, their volume, temperature and pressure.

Representational form and function of models. *Maps, diagrams and tables* are examples of static two-dimensional (2-D) models that facilitate visualization of phenomena or things. Examples of these are the periodic table, weather maps, circuit diagrams. *Concept-process models* are the multiple models used, simultaneously, to describe various states and/or spatio-temporal conditions of a phenomenon. These are often word models. *Simulations* are models that assemble the complexities of dynamic processes in such a way that they may be experienced without the risk, time or cost implicated by the real thing. Timely examples are global warming models and economic models.

As an aside, note that Gilbert (2004) lumps together these two notions of function and form and focuses on the modes used to represent and share scientific models: concrete, verbal, symbolic, visual and gestural. Physical three-dimensional models describe the *concrete mode*. Descriptions of entities and relationships between them, explanations of processes constructed as analogies or metaphors, are examples of the *verbal mode* that models can take. For instance, consider a verbal and/or written description of the nature of balls and sticks representing molecular structures, or the verbal and/or written analogy of electricity as the flow of water. Symbols, formulas, equations, and mathematical expressions make up the *symbolic mode*. While two-dimensional representations such as maps, graphs and animations make up the *visual mode*. Rounding these off, the embodied physical expressions of one's understanding can be displayed in the use of our physical bodies, hence, the *gestural mode*.

Ontological and epistemic considerations of models. Lastly, models can acquire ontological and epistemic status, i.e., their role in allowing us to think and communicating our ideas about the world and about knowledge. It is generally believed that in cognitive functioning we construct internal representations of the world, mental models, that are personal interpretations which help us to explain the world, as we experience it, and determine what actions to take (Johnson-Laird, 1980; Vosniadou & Brewer, 1994). As such, they are equivalent to the socio-cultural notions of common ground and development of norms, described earlier.

In fact, we might consider evidence of common ground, the norms and values we take as shared, as evidence and indicators of Gilbert's (2004) ontological and epistemic characterizations of *expressed models* (those we use to communicate our ideas with others) and *consensus models* (those we share with others). Such mechanisms allow us to work co-operatively and/or collaboratively with others.

Gilbert (2004) also talks about *scientific models and historical models*, which reflect current states of agreed-on thinking by the scientific community. These are the common ground that science community as a whole agree to and operate within. These are the values, norms and beliefs that science students must acquire if they are to participate as true members of the science community. These are the values, norms and beliefs that we want our students to practice in the science classroom and lab, as they become members of those smaller science communities. Such scientific models are the hallmark of ones identity as a scientist, or a student scientist. They are the "right" way of thinking for reasoning about science and the "lived actions" for the participation in science.

2.2.2 The Use of Models in Science Instruction

Model-based reasoning is arguably an important part of scientific reasoning and involves creativity, which cannot be reduced to mere algorithmic solutions (Magnani & Nersessian, 1999). Research suggests that the active engagement in model construction and use of these models in authentic scientific inquiry promotes understanding of the nature of science, as well as life-long learning (e.g., Linn & Muilenberg, 1996; Sabelli, 1994). The literature on models and modeling related to learning can be divided into two categories. One perspective focuses on the use of pre-existing models (Raghavan & Glaser, 1995) and another, which focuses on the active construction and use of models by the learner themselves (e.g., Gobert & Clement, 1999; Penner, Giles, Lehrer & Schuable, 1997).

Gobert and Discenne (1997) tell us that students with more sophisticated epistemologies of the nature of models are better able to make inferences about other causal mechanisms. Others (e.g., Charles, 2003 dissertation) suggest that student's capabilities implicate their ability to use and learn from models.

Yet another consideration when it comes to learning with model is the effect of the representational mode used. Different representations offer different cognitive *affordances* and may require different capabilities and support. For instance, Gobert (2003, NARST) suggests that diagrams do not necessarily facilitate student's understanding because of the added cognitive load (Sweller, et al., 1990). Additionally, domain knowledge is required to guide the search processes through this representational mode in order to understand the relevant spatial, causal, dynamic, and temporal information (Lowe, 1989; Head, 1984; Gobert, 1994; Gobert & Clement, 1999). Scaffolding is thus necessary to support students' learning with such models.

2.3 Difficulties in Learning Physics

To start we know that students perform very poorly when asked to solve qualitative physics problems though they may demonstrate mastery in solving seemingly similar quantitative physics problems (Halloun & Hestenes, 1985; Hake, 1998). Research shows that even college aged students have difficulty constructing conceptual understandings of concepts of force, motion, and acceleration (Hestenes, 1992; Redish, Saul &Steinberg, 1998). Such conceptions of the physical world, as well as many other science concepts, are difficult to change with traditional instruction in physics (e.g., diSessa, 1993; Pfundt & Duit, 2003; Ram, Nersessian & Keil, 1997; Thornton, 1995; 1997). This may be because these concepts are constrained by strongly held naïve conception of how the world works. And, made all the more challenging because of the everyday uses of those concepts that lie at the heart of the causal explanations, i.e., force, acceleration, momentum, etc. To reorganize, or to replace[2], these conceptions and gain a deep understanding, which can be readily applied across contexts, requires a great deal of effort on the part of the learner (e.g., Hmelo-Silver, Holton & Kolodner, 2000). Those findings have lead to theories of how these misunderstood concepts develop and what the process of change may involve (e.g., Chi, 2005; Chi, Slotta & deLeeuw, 1994; Slotta & Chi, 2006).

2.3.1 Conceptual Change

Conceptual change models fall into two primary groups (Nersessian, 1989); the more conventional view known as accommodation models, described below, consider the conceptual ecology of the learner but assert that, through reason, the more fruitful explanation will be adopted.

Piaget (Inhelder & Piaget, 1958) proposed that the changes in children's conceptions of the world, from naive to scientific views arise as a result of developmental stages resulting from the acquisition of formal reasoning structures (INRC). Thus, as a result of biological maturation, learners acquire *domain-independent* skills that allow them to reconstruct their conceptual structures by a process of assimilation and accommodation. According to Piaget, this restructuring will happen when learners are confronted with anomalous information or experience. Rumelhart and Norman (1981) suggested that as learners mature in their

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[2] This question is one of big theoretical debates that exist in the field of conceptual change. Like others before us, we do not wish to take up this line of reasoning at this time, but limit ourselves to claiming that change of some sort is required for learning of certain conceptions, particularly in the sciences. And, the concept of force and motion is one that has been long documented as concepts that call for conceptual change.

understanding of a topic, they progress through an initial *accretion* stage (the acquisition of new-information by its addition to pre-existing conceptual structures), an intermediate *tuning* stage (the slow modification of conceptual structures), to a final *restructuring* phase (the construction of new schemata by the subsumption of surface features by general principles).

Posner, Strike, Hewson, and Gertzog (1982) proposed the first model of conceptual change relevant to science education. They proposed that students change their conceptions when they become dissatisfied with their conception and are confronted with an alternative intelligible conception and when the new conception is plausible and fruitful.

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

The more recent (restructuring models) emphasize the restructuring of underlying “structures” or “mechanisms”. The restructuring models posit that it is the very nature of the explanation, the underlying beliefs of causation that need to be addressed, not only the declarative knowledge. Several researchers, investigating conceptual change in physics domains have posited restructuring models of conceptual change: (1) Vosniadou’s “framework theories” (e.g., Vosniadou & Brewer, 1994), (2) diSessa’s “causal net” (diSessa & Sherin, 1998), and (3) Chi’s “ontological beliefs” (Chi et al. 1994). Although these researchers disagree on several fundamental points related to how coherent or fragmented these naïve “theories” or beliefs are, they agree that these beliefs need to be altered in order to repair and/or remove misconceptions.

Caveat. Though we acknowledge that it is likely that learners hold certain conceptions about phenomena that can be described as mental models (i.e., internal representations), we do not explicitly attempt to ascertain these pre-conceptions, nor do we attempt to interpret our findings as a shift or change to these internal representations. Instead, we describe the capabilities and skills that learners demonstrated during and after instruction. My view on learning is that of a situated socio-cognitive process that takes into account both the individual learner and others within the activity system of the classroom or the working group. In fact, the learner working by herself might constitute multiple selves as they generate questions to be answered and problematize the phenomenon in question.

2.4 Assessing Conceptual Change in Physics

Many researchers consider that the underlying problem in science education is that many students do not acquire a meaningful understanding of science (Eylon & Linn, 1988; Cavallo, 1991; Alexander & Kulikowich, 1992). Students tend to rely on memorizing isolated facts and procedures rather than on relating ideas and constructing a coherent body of scientific knowledge. They also have extreme difficulty in abstracting key ideas, discerning relationships between ideas, and integrating these ideas to their prior knowledge to form a coherent framework (Novak & Gowin, 1984). Thus, students have difficulty transferring what they have learned in the classroom both to other courses in the same discipline and to "life" situations. Thus, meaningful learning requires that students change their conceptual structures. However, studies from a variety of perspectives (misconceptions, alternative conceptions, naive beliefs, *etc*.) have shown that college students often have great difficulty in changing their naïve conceptions of the physical world and acquiring a scientific understanding of force, motion, acceleration etc. (Clement, 1982; DiSessa & Sherrin, 1998; Duit, Roth, Komorek, & Wilbers, 1998; Gardner, 1986; Hake, 1998; Halloun & Hestenes, 1985; McDermott, 1984; Van Heuvelen, 1991).

The development of instruments such as the Mechanics Diagnostic Test (MDT) developed by Halloun and Hestenes (1985), the Force Concept Inventory (FCI) developed by Hestenes, Wells, and Swackhammer (1992), and the Tools for Scientific Thinking: Force and Motion Conceptual Evaluation (TST developed by Thornton (Thornton, 1995; 1997) which assess conceptual understanding of Newtonian physics has convinced most researchers and physics instructors that indeed there is a problem with physics instruction. There are at least two streams of research in how students learn physics. Firstly, many American Universities have established programs of research on physics education within physics departments (van Aalst, 2000)[3]. Secondly, researchers in the Learning Sciences, Cognitive Science, and Educational Psychology also have a long tradition of investigating issues concerning how students learn physics (Caramazza, McCloskey, & Green,1981; Chi, Feltovitch, & Glaser, 1981; Chi & Slotta, 1993; diSessa & Sherrin, 1998; White & Fredericksen, 1998). However, these two groups of researchers rarely quote each others' research. Thus, one of our goals in the proposed research is to integrate the sets of literature and methodologies and to introduce it to Cégep Physics faculty that may not be aware of this research literature.

2.5 Using Models to Teach Physics

While folks such as Hestenes (2000) talk about using models to teach physics, such instructional approaches do not necessarily harness the potential that inquiry-based instruction and project-based instruction offers. One approach to teaching science using physical models that we are most familiar with comes out of the design-based inquiry approaches to learning. Learning by Design (LBD; Kolodner, 1997; Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, Puntembakar, Ryan, 2003) is built on a model of learning referred to as *case-based reasoning* (CBR: Kolodner, 1993; Schank, 1982, 1999), which suggests the kinds of experiences (cases) and reasoning skills[4] students should engage in to learn deeply. And, describes the possible cognitive processes and knowledge representations required for transferable learning (Kolodner, Gray, & Fasse, 2003). CBR further suggests the following: identification of gaps in knowledge through feedback on one's decisions: recognition and explanation of gaps between prediction and results; reflection on and indexing of experiences for future use; multiple opportunities to cycle through application of learning, designed as iterative refinements; encouragement and scaffolds to promote reuse of prior experiences – their own and those of others.

Typically in the LBD curriculum, students build three models: (1) Coaster car, (2) Balloon car, and (3) Rubber Band car. In the process students learn physics concepts and use

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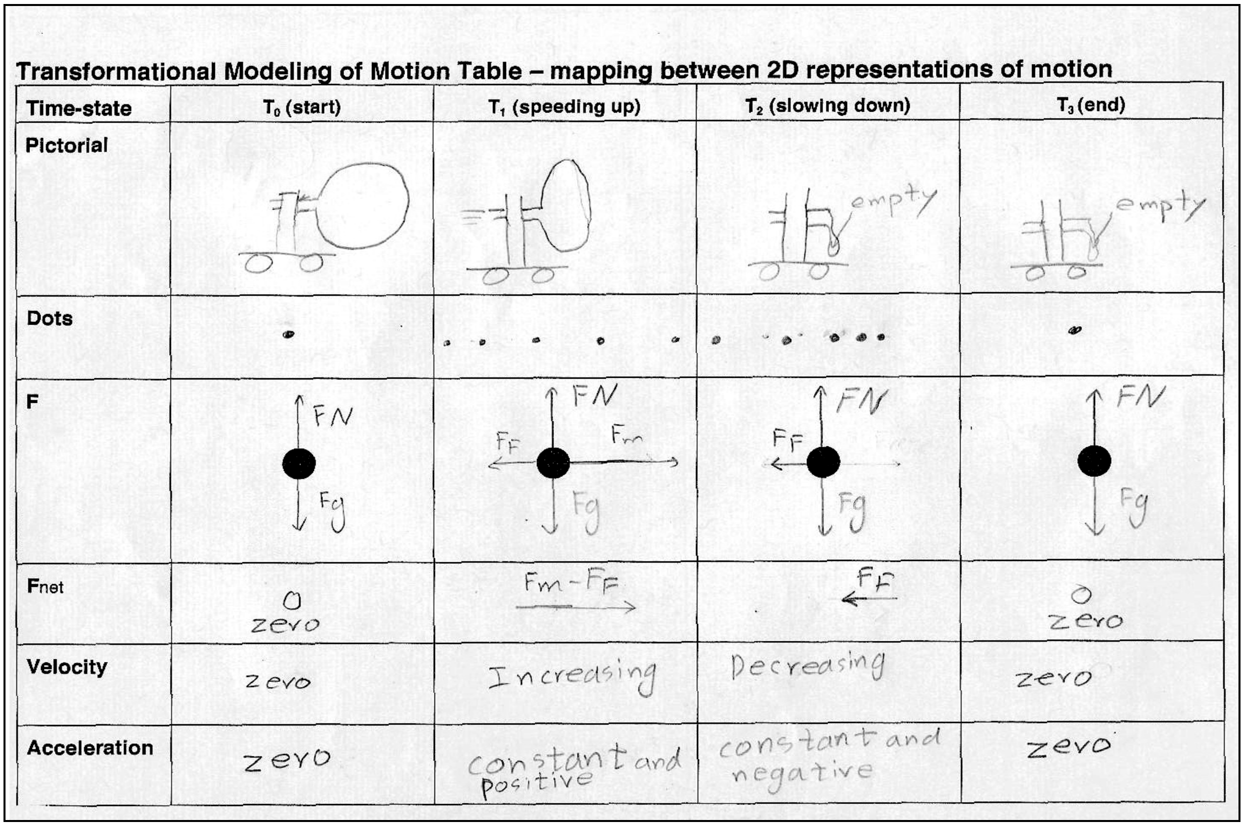
[3] See http://www.physics.umd.edu/perg/homepages.htm provided by the Physics Education Research Group, University of Maryland, College Park campus.

[4] In CBR learning implicates interpreting new experiences, and reinterpreting and *reindexing* old experiences to make them more generalizable, to create new explanations that connects one's current goals and actions with resulting outcomes.

math and physics notations (e.g., sine and cosine, free body diagrams). In particular, a representation called the *Motion storyboard* is introduced midway through coaster car segment to help students visualize the forces acting on the cars[5]. Our adaptation of the motion storyboard produced a new mediating tool, which bridged between the physical model and the abstract scientific concept. We refer to it as the *model-bridging* storyboard tool (NB. we also refer to it as the model-bridging tool, or, simply, the storyboard; see Figure 0) because we conjecture that it would scaffold students' ability to reason about models. Specifically, allowing them to link theoretical abstract models (i.e., Newton's Laws) to reasoning about the results produced by their physical models.



Transformational Modeling of Motion Table – mapping between 2D representations of motion

Time-state	T_0 (start)	T_1 (speeding up)	T_2 (slowing down)	T_3 (end)
Pictorial			empty	empty
Dots	•	• • • • •	• • • • • •	•
F	FN Fg	FN FF Fm Fg	FN FF Fg	FN Fg
Fnet	0 zero	Fm - FF	FF	0 zero
Velocity	zero	Increasing	Decreasing	zero
Acceleration	zero	constant and positive	constant and negative	zero

Figure 0. Adapted motion storyboard – bridging between physical and abstract models.

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[5] It is a graphical representation developed by Mike Ryan, an LBD researcher and curriculum developer. According to Ryan, the motion storyboard allows students to "slow down" the phenomenon of their vehicle's motion and pictorially describe it in discrete time frames or chapters – not moving, beginning of run, during the run, and end of run. This 2D representation is later mapped to traditional force vector diagrams, which interpret these frames as changes in force and acceleration.

Research in LBD classrooms has found that students learn general Newtonian physics concepts better than students in comparison groups (Charles, Karkin, Kramer & Kolodner 2006; Charles & Kolodner, 2007; Kolodner, Fasse & Gray, 2002). In their study of an LBD classroom, however, Leonard and Derry (2007) tell us that the students did not refine their existing conceptual models (i.e., undergo conceptual change). They propose that making students' science conceptual models more explicit and the objects of cognition and inquiry may help to remedy this shortcoming.

Though models clearly form a basic component of the LBD instruction, their use as tools of conceptual change has not been a major consideration. Thus, in this current study we explore the potential of the models and the implications of using the physical models to introduce conceptual notions of force and motion. As well we examine what happens when the instruction explicitly describes models and modelling as a tool in science learning.

2.5.1 Need for Scaffolds When Learning with Models

Following up on Leonard and Derry's (2007) recommendation, other researchers have commented on the need for scaffolding student learning with models. Raghavan and Glaser (1995), showed, in studying the development of students' reasoning skills when instruction included explicit discussion of models as tools in science, that their 6th grade students developed and improved model-based reasoning skills related to predicting, testing and evaluating ideas. They suggest that scientific models need to play a more active role in order for students to develop a deeper conceptual understanding of their use in science.

Treagust, Chittleborough and Mamiala (2004) also propose several teacher strategies that were useful for learners: (1) using 3-D models followed by 2-D models had pedagogical merit (2) repeated practice at representing and naming compounds resulted in learning chemical subject matter, (3) collaborative tasks promoted discourse and peer-learning, but (4) using computer simulations proved superficial maybe because it was done outside of class.

Gobert and Buckley (2000) suggest certain types of scaffolding framework for learning with models. These include the following:

1. Representational assistance scaffolds – guide students understanding of the

representations or domain specific conventions within the model (e.g., means of arrows in FBD).

2. Integration of pieces of the model – supports students by using reflective questions, tasks, explanations intended to promote integrating of components of the model.
3. Model-based reasoning supports – supporting students in reasoning and with their model revision through specific tasks.
4. Reconstruct, reify and reflect – supporting student in their reflections of what they have learned, reinforcing it and reflecting again to move to a deeper level of understanding (probably similar to stuff that Janet talks about with CBR).

We designed scaffolds for our instructional unit keeping these guidelines in mind (see Promoting Conceptual Change Using Scientific Models in Physics workbook). To start, we put our models front and center so that they could play a more active role in helping students learn about Newtonian physics. Next we began with physical 3-D models followed by 2-D models to help students transform real world phenomena in a stepwise manner. In other words, slowing things down and moving from the many complexities of the real world to the simplified and abstract setting of the model-bridging storyboard. We also had students collaboratively engage in repeated practice with the different representational modes and the subsequent transformation. We used questions in the workbook to prompt reflection on the underlying causal mechanisms and hopefully support the types of conversation that we believe are necessary for deep learning. In accordance with Gutwill, et al. (1999) we designed representation transformative tools to mediate and promote understanding of dynamic processes.

2.6 Summary of Theoretical Background

Learning involves more than cognitive capabilities. It includes social and cultural aspects that come together in the jointly shared tasks and jointly shared spaces we create when designing instruction and tools with affordances for learning. Learning also includes the development of common ground, shared models of the task involved and the means of shared representations and inscriptions (what Vygotsky refers to as signs and symbols). In science education, such common ground involves establishing, negotiating and mutually constituting joint and shared meanings of scientific practice as well as scientific representations, which include scientific models.

Using models as a way to learn science seems to be profitable because of the depth of understanding it brings both in terms of the content being learned and the epistemology of science itself. However, the literature tells us that learning with models is not an easy task and we must make accommodations for certain difficulties. Furthermore, learning physics is further complicated by concepts that stubbornly resist traditional instructional methods (i.e., require conceptual change).

In this study we address these issues by modifying an instructional approach that uses physical models to teach science. To this we add certain representation transformative tools (the model-bridging storyboard tool), all within an environment that fosters collaboration. Through these means we prepared students to participate within a small community of scientists and engage in the types of activities and associated discourse that we believe promotes science learning.

This report describes what we did and what happened as a result. The results are divided into two volumes. Volume I is a case study of a small sample of students using the instructional intervention, (based on the LBD approach) previously described briefly. Volume II is a quasi-experimental accounting of students' conceptual learning of physics assessed using the Force Concept Inventory (FCI; Hestenes, et al., 1992) instrument. We continue next with the methods section, which describes both studies.

RESEARCH DESIGN AND METHODOLOGY

This research is divided into two studies: Study 1 (the Case Study) and Study 2 (the FCI Study). This results of the Case Study are presented in this part of the report, Volume I, the results of the FCI Study are presented in Volume II of the report.

Study 1 was designed as an ethnographic case study. We collected both video and written data from several small groups of first year science students, working collaboratively, over a period of six weekly one-hour sessions. All groups observed were in the first year of the science program but some were enrolled in the honours science program while others were enrolled in the preparatory science program. Study 2 was designed as a pretest and postest investigation and collected questionnaire data from the entire cohort of first year science students. These two designs allowed us to answer our research questions.

3.1 Research Setting and Participants

This research was conducted at a large, urban, multi-cultural and ethically diverse post-secondary educational institution, Dawson College, situated in the largest metropolitan city in the province of Quebec, Canada. This institution is part of the educational system referred to as *Collège Études Général Et Professionnel* (commonly called Cégep). The function of the Cégep is to serve the needs of the broadest possible community by providing both 2-year pre-university programs in the Arts and Sciences, as well as highly specialized 3-year professional programs. The pre-university programs are roughly equivalent to grade 12 and first-year university found elsewhere in Canada and in the United States.

The students participating in this study were all first year science students attending Dawson College. The pre-university Science program at Dawson is typical of those at other English colleges in the system. Entering students are required to have a minimum of 70 percent on their high school leaving certificate and certain prerequisite courses in math and science (Math 536 (Functions), Physics 534 and Chemistry 534). Depending on their high school grades, students may be eligible for one of the three Science programs, honours (First Choice), regular, and preparatory (DSP & ESP).

General admission to First Choice Science program (officially referred to as “profile”) is by invitation. To be considered for admission for this program, the following grade requirements must be met: 80% Overall Secondary V Average; and, 80% in each of the Secondary V Chemistry, Mathematics, and Physics. As this program is competitive, however, an 85% in these courses offers a more realistic prospect for admission. However, not all students who are invited accept the offer, therefore there are some students who qualify for honours classes who choose to remain in the “regular” program.

To be required to take the Preparatory Science program, students have less than 70% in their math and science courses, or they have not taken one or more of the required math or science courses in high school. Typically, the ratio of honours, regular and preparatory classes is 20:60:20 (though the actual proportion of students, in this case, was somewhat less in the preparatory classes).

It is important to note that some students in the “regular” science program have similar profiles to some students in honours and others to some students in DSP classes, hence our belief that the results of our study may extend across all three cohorts of students in the science program. For our case study research we selected students in the honours and preparatory Science programs for several reasons. Firstly, we hoped to be able to comment on the development of capabilities and participation structures of these diverse populations, which we believe also sheds light on students with similar profiles who are part of the larger cohort of “regular” students. Secondly, in each of these two profiles there was one class taught by the same teacher, therefore we only needed to organize with one teacher, which helped us control and better interpret the teacher effect.

Case Study. Sixteen students in total took part in the case study project[6] (9 Honours, 1 Regular, 5 Preparatory). The students were grouped and scheduled according to their science program – Honours Science or Preparatory Science (we will refer to them simply as honours or preparatory).

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[6] Note there was one DSP student (Team 1) who dropped out after session 3. And, there were two DSP students who were not members of Mr. Trent’s class who wished to participate but did so as an unofficial case study.

FCI Study. The Force Concept Inventory (FCI; Hestenes, Wells, & Swackhammer, 1992) was administered to 390 students enrolled in 14 sections of Physics NYA, which is a compulsory course in mechanics for first year science students at Cégep. Of these 390 students, 284 (Females = 142; Males = 142) signed a consent form, therefore we report on these alone. The 14 sections represent three different cohorts of students: 3 Honours sections, 8 Regular sections, 3 preparatory sections.

3.2 Procedure

3.2.1 Case Study

The procedure used in this case study was a standard pre-intervention assessment, instructional intervention and post-intervention assessment design. The instructional intervention (referred to simply as intervention hereon) and all working with the physical models took place outside of class time. All physics content was taught by the students' assigned instructor in regular class time. The original plan for the intervention sessions was that there would be five 60 minute weekly sessions in which the same students would meet and work in established teams. We believed that this 60 minute period would be sufficient for students aged 16-18 to assemble and run tests of a different model vehicle each session. As it turned out, however, it took students more time to get going with the building and testing of their models, thus, we reduced the number of models constructed by one, and added an extra session. We present the instructional intervention as it actually happened.

Recruitment of students. We recruited students from their respective honours and preparatory classes taught by Mr. Trent (pseudonym used). Mr. Trent was a newer member of the physics faculty and well liked by his colleagues and students alike. He had a strong physics background and was particularly supportive of the research using instruction that would use models because he also advocated this way of thinking in his classroom.

Early in the fall 2006, using a typical recruitment technique of a short in-class presentation by one of the research team, we solicited participants from Mr. Trent's two classes. In this presentation we invited interested students to a formal information evening, which was designed to provide background information on the project as well as introduce students to the notion of scientific models and their role in reasoning about physics. Additionally, the evening was designed to collect consent forms and baseline pre-instruction data related to the students' epistemology of models (see Appendix A).

Two information sessions were organized for after classes, early evening, to accommodate the students' hectic schedules, and refreshments were arranged as a courtesy and motivator, due to the time-of-day. The first information session had 9 students, all of whom continued on with the project. The second information session was postponed due to an unprecedented tragedy at the College (shootings of September, 13). Surprisingly, we did not lose too many students who had initially shown interest in the research, and all 7 students who attended the evening information sessions continued forward with the research.

Assigning students to research groups. Recall that the students were grouped and scheduled according to their science program – Honours Science or Preparatory Science (we will refer to them simply as honours or preparatory). This decision was made for two reasons: (1) for practical purposes and scheduling, students' availability was more likely to overlap if they were in the same program; (2) from a theoretical point of view, we believe that homogenous groups would work together better (e.g., Barron, 2003.).

The honours grouping was composed of three teams, each 3- 4 students (Teams 2, 3, &4). The preparatory grouping was composed of two teams, one of 4 students (Team 1) and one of 2 students (Team 5). Team assignment was based on observable social affiliations between students and not on theoretical grounds[7].

All three honours teams met on Wednesdays between classes, roughly in line with a lunch break. While the two preparatory teams meet on Thursday afternoons, between classes for some, but roughly at the end of the school day for others. Team 5 did not start at the same time as the others and did not complete all sessions, for this reason we will not include their data in our description of the teams though their participation in session 6 (whole class debriefing with all teams in the same time period) does have implications for the level of discourse and learning.

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[7] Note that the sole regular student was reassigned from the preparatory team to one of the honours teams after the second session.

3.2.2 FCI Study

The FCI pretest was administered early in the Fall 2006 semester, approximately between weeks 2 and 3. The FCI postest was administered after the units of force and motion were completed by all sections, approximately weeks 11 to 13. In both instances, generally, it was administered to students during the last 30 minutes of a physics lab, with the teacher's permission. However, in at least one section, the teacher asked for the questionnaire to be given out at the beginning of class. We do not believe that this difference affected the results since in all instances all students were allowed to complete the questionnaire.

Note that the ARLIN test of Formal Reasoning was administered in a similar fashion at the end of the semester, but this time in the Chemistry lab or Math class. Again depending on the teacher's permission. Meanwhile, the College administered the other assessment measures, such as the Nelson Denny, as part of the students' entrance requirements.

3.3 Background to Case Study instructional design

The instructional intervention used in this study was adapted from the Learning by Design approach (LBD: Kolodner, et al. 2003). To start, we believed that our population of first year Cégep science students would have different capabilities and skills than the middle school students who traditionally have been the focus of prior design-based instruction research (e.g., Charles & Kolodner, 2007). Specifically, we hypothesized that Cégep science majors would have greater domain knowledge and would have a more developed understanding of scientific reasoning skills. Secondly, we wanted to extend the research on design-based instruction and address some of the concerns that design as an instructional tool sometimes misses the mark and does not directly consider certain difficulties related to the construction of conceptual models of the scientific phenomena (e.g., Lenoard & Derry, 2007). Therefore, we explicitly emphasized the role of models in science and explicitly attempted to link the model-building activities with the theoretical models of physics. Lastly, we wanted to start unpacking the cognitive and social affordances built into the richly designed LBD approach. Thus, to identify some of the dependencies inherent in the cognitive activities (e.g., scientific reasoning, reflection) and social practices (e.g., private group discussions, public whole-class presentations) we selected certain aspects of the LBD approach and left out others. In doing so, we hoped to begin the process of identifying the necessary and sufficient components that make up this design-based instruction, thereby adding to this theoretical model of instruction and learning.

3.3.1 How This Intervention Varied From LBD

The issue of what to keep and what to change was an important concern for the research team. Foremost, the timeframe would have to be significantly reduced. A traditional LBD approach takes approximately 65 hours, with 30 of those hours devoted to the content unit. We knew from the start that we would have must less time. Taking into account that the regular course would be teaching the physics content, we were able to design an intervention that focused exclusively on the role of model and the model building and testing. In short, we did not attempt to teach physics principles, nor did we attempt to teach how to design and conduct scientific experiments (i.e., the scientific method). With this, our intervention consisted of six sessions in which groups of students worked with different models demonstrating the properties of the selected topic in classical mechanics (e.g., acceleration).

In regard to the two-cycle of design and investigate, we modified this feature and concentrated on the structured investigations, with a hint that these results could be useful for a future design project. As a token nod to LBD's challenges, we decided to have a wrap-up assignment that allowed students to bring these ideas together in a fun and motivating pen and paper activity. When it came to the issue of practices, we believed that some aspect of the private small group and public whole-class activity structure were important to the social learning that we see in LBD classrooms, therefore we attempted to maintain this feature. Next we describe the actual intervention used, as well we provide a copy of the workbook used (see Enclosure). Note that the enclosed workbook incorporates the improvements suggested from the case study experience.

3.3.2 Intervention Instructional Unit - Six Plus One Sessions

In the introductory session, students were introduced to the topic of scientific models as one of the principle tools of modern science. They were shown examples of how scientists have used models as a central focus for thinking about phenomena and conjecturing about the mechanisms behind them. The students were also introduced to the tasks of building physical models as a way to help them think about the physics they were learning in their course on mechanics. At the end of this session, students were placed into work groups for their future activities. Lastly, they were presented with a formal definition of models and asked to consider how they might go about constructing a model of a topical phenomenon (see Appendix B.1).

In sessions one and two, students working in groups of 3-4, were to investigate the affects of their assigned variable on the performance of a model car (the independent variable). They were to start by building a coaster car with simple tool (e.g., pliers, masking tape), using simple materials (e.g., *foamcore*, threaded rods, nuts and bolts), then vary the feature in question (e.g., the wheels' surface, the circumference of the wheels, the weight of the car). In doing so, they were to design and conduct a controlled experiment, which would provide reliable data that would be shared with the other students in the research project. These results were to be posted in a public access space on a dedicated on-line conference. Additionally, students were asked to take a look at these results and use them to make their final decisions as to what features of a coaster car might be most responsible for its peak performance.

In session three and four, using the same chassis of the coaster car, the students were to continue investigating motion, this time with the help of a balloon "engine" propulsion system. They were not required to build, per se, but provided with a package containing the assigned variable to investigate (e.g., different numbers of balloon engines, different number of layers of balloon, differently sized straws for the balloon engine). Again they were asked to design an appropriate experiment, run their test and collect data, which was again to be placed in the online conference. The students were also introduced to a representation transformative tool, one that we refer to as the model-bridging storyboard. They were asked to complete this document, in the process, discuss the different representations of force and how these relate to the physical model of the car and its propulsion systems. This task along with the construction of the storyboard promotes students' reflection of salient characteristics of models, we hoped (Clift, Houston, Pugach, 1990; Schon, 1987).

In session five, the students were to use the SIMCARS (Vattam & Kolodner, 2005) software developed specifically to match the LBD activities, and adapted specifically based on feedback from the pilot study conducted prior to this research. SIMCARS simulated the three types of cars that students would have been able to test or observe, but this time they had the opportunity to run their test under ideal conditions, and without friction (see Appendix B.2; and enclosed DVD).

The intention of this experience was to provide another type of model of the same phenomena so that students would begin to understand that the same model could be represented with different media, which allowed for other types of features to be observed. Additionally, the simulation also featured acceleration and velocity graphs, which provided yet another way that students could represent the abstract notion of forces. They were asked to think and talk about these different representations while working with the simulation.

Session six was the final formal session and students were asked to brain-storm on a design problem. They were given a scenario involving certain climatic constraints and asked to consider how to design a vehicle taking into account its propulsion system and the mechanisms that would provide the requisite motion. Before the end of the session they were to share these ideas with the rest of the groups in a public face-to-face chat session. See Table 2 for the schedule of the intervention.

Table 2. Case Study Intervention Schedule.

Week	Instructional Objective	Level of Situatedness
Pre-intervention introduction	Introduction to models and modeling – lecture and group formation	
Week 1-2	Modeling activity starts with how a vehicle moving only under the force of gravity works (*coaster car*). What affects it? What do you learn?	Highly situated - Build & test a coaster car
Week 3-4	Modeling activity - a vehicle propelled by propulsion force from balloon &/or rubber bands (*balloon car & rubber band car*). What affects it? What do you learn?	Highly situated - Build & test a balloon car

Week 5	Working with SIMCARS. What's different between physical models and simulation? How can you explain the differences?	Moderately situated – transfer to simulated environment
Week 6	Post design activity module. What did you learn from the experiences? *Situated* problem (build a hypothetical car)	Highly situated – problem solving
Post-intervention interview	Questionnaire – Describe what is a scientific model? When and why might you use them? What is their function/role in understanding science?	Weakly situated – problem solving

3.4 Data Collection

We used a variety of assessment methods in this project - some at the group level and others at the individual level. With the extensive corpus of data we did not have time to analyze them all. (NB. For the readers' convenience, we catalogue these corpus in Table 3).

3.4.1 Case Study Data and Group Assessment Measures

An ethnographic method was used to collect data from the six intervention sessions of the case study. Students were videotaped and field notes were made by two of the researchers. Additionally, we collected a variety of written work produced by the students as part of their group work – e.g., physical models, model-bridging storyboards, written explanations in shared workbook, online communication – (see Appendix C for some samples).

3.4.2 Epistemology of Models Assessments

We used several assessment measures to determine students' epistemology of models: (1) epistemology of models questionnaire developed for *Concord Constorium Pedagogica* series; and (2) open-ended questions (adapted from Gobert & Discenna, 1997). Both these measures were administered as pre and postest.

The epistemology of models questionnaire. The epistemology of models questionnaire based on the seminal work of Grosslight et al., (1991). This particular 24 item questionnaire was developed by Janice Gobert and Barbara Buckley and used in the *Concord Constorium Pedagogica* series as a pre-instruction and post-instruction instrument. It is divided into five categories of beliefs: (1) use of models, (2) changeability of models, (3) isomorphic quality of models, (4) features of models, and (5) need for different representational forms of models. The students are asked to answer the questions based on a scale of 1 to 5, with 1 being strongly disagree and 5 being strongly agree. Reportedly, these questions are designed to reveal the students' understanding of models and their use (see Appendix D.1).

Open-ended interview questions about use of scientific models. A questionnaire was developed to collect students' epistemic beliefs about models, both as a pretest and postest. In the pretest, the questionnaire was administered in written form and also included demographic information about the student. For example, questions about their experiences related to science and extra-curricular interests relating to science (see Appendix D.2).

In the postest, the questionnaire was administered as part of an interview. Also included were other questions: (1) the students' understanding of the physics concepts related to Newton's laws, (2) their feelings about the intervention, and (3) their self-reported sense of self as a result of participation in the research project (see Appendix E).

3.4.3 FCI Questionnaires

The FCI questionnaire is a 31-item instrument designed to assess students understanding of basic concepts of Newtonian Physics: Forces, Kinematics, and First, Second, and Third Law (see Appendix F.1 for abridged FCI pretest and postest). Its aim is to evaluate students' knowledge of these concepts and is interpreted based on a 3-stage model of evolution of conceptual understanding of Newtonian Physics. It has been used with more than 20,000 high school and university students. It is reported to be independent of mathematics performance, high school grades, socio-economic status, teacher competence but not gender (e.g., Lorenzo, Crouch & Mazur, 2006; McCullough, 2004). It reportedly shows changes in response to instructional strategies. It is a highly regarded assessment measure, which is credited with motivating much interest in research in physics education and conceptual change in physics.

We used the full 31-item questionnaire in our pilot study. Results from that study, as well as detailed classifications of all 31 items (see Appendix F.2), allowed us to construct an abridged version of the FCI questionnaire (21 items), which our analysis shows is highly correlated with the full version. In this abridged version, 11 items were unique to the pretest and postest, and 10 items were repeated. We constructed this version for two reasons. First, because the questionnaire was distributed during class time, we needed to respect the allotted time without penalty to eliciting the students' true understanding. Second, we believe that by have both new and repeated questions we could better address test-retest reliability issues.

With the permission from the case study students we collected their individual results from the Force Concept Inventory (FCI) pretest and postest that was conducted in class by the other part of the study. We analyzed these data and describe them with a normalized gain score. To avoid ceiling and floor effects, *normalized gains* (Hake scores) in the FCI are compared. Normalized gains are defined as:

$$g = (\text{Post T} - \text{Pre T}) / (\text{max T} - \text{Pre T})$$

Among compelling arguments given for using normalized gains (g), is the reported finding that g is *uncorrelated* to pre-test scores (Hake, 2002) and therefore gives a better description of the conceptual gain due to instruction. In contrast, post-test scores are highly correlated with pre-test scores, which would be expected if no instruction were present.

3.4.4 Other Assessment Items Collected

ARLIN Test of Formal Reasoning (ATFR). The ATFR is from Slossan Educational Publications, Inc. (Arlin, 1984). It is a 32- item paper-pencil multiple choice test (see Volume II Appendix) that assesses both the students' general level (low concrete, high concrete, transitional, low formal, high formal) and specific level on the following eight reasoning skills described by Inhelder and Piaget (1958). The second author has used it on previous occasions to measure science students' level of formal reasoning (d'Apollonia, 2004).

1. *Multiplicative Compensations*: Reasoning about effects of two or more variables that

have an inverse relationship. That is gains or losses in one variable are compensated by gains or losses in the other.

2. *Correlations*: Reasoning whether two events are or are not related and if they are, about the strength of the relationship
3. *Probability*: Reasoning about the likelihood that one or more events will happen.
4. *Combinations*: Reasoning that generates all possible combinations of a given number of variables.
5. *Proportions*: Reasoning about the equality of two ratios that are proportionally related.
6. *Forms of conservation beyond direct verification*: Reasoning about the influence of one variable on a second which is not directly observable but must be inferred
7. *Mechanical equilibrium*: Reasoning simultaneously about the influence of many coordinated variables that affect equilibrium processes.
8. *The coordination of multiple frames of reference*. Reasoning about the coordination of two related systems, each involving a direct and an inverse operation. It represents a type of relativity of thought.

Nelson Denny Reading Test. The Nelson Denny Reading Test (Brown, Bennett & Hanna, 1981) is a standardized testing instrument. This test is composed of two parts. The first part is a vocabulary section of 100 items each with five answer choices and is limited to 15 minutes. The second part is a comprehension section consisting of eight reading passages and a total of 36 questions. The time limit for this section is 20 minutes. The reliability coefficient of the vocabulary score is determined to be 0.92, whereas the comprehension reliability coefficient is reported at 0.77 (for examples of the test and more detail see Brown, Bennett & Hanna, 1981). The records provided both "raw" scores for the students as well as the grade equivalent of these. For example a raw score of 70+ for vocabulary is considered at grade 16 (above average), while scores of 55+ on the reading comprehension are at grade 16 (above average).

High school and college grades. Lastly, we asked students' permission to collect their high school grades. As well as collected their grades from their other science course and final R scores.

Document Literacy questionnaire. (see Volume II Appendix)

Table 3. Summary of data sources for both studies.

Item	Data Sources	Location & Timeframe	Numbers	Type of assessment
1	Conceptual knowledge of forces (abridged FCI)	In class (14 sections) Pretest	284 students	Individual
2	a. Demographic questionnaire	Intro session Pretest	16 students	Individual
	b. Epistemic questionnaire	"	"	Individual
	c. “What are models” questions	"	"	Individual
3	Video tape sessions & transcripts	Sessions 1-6	5 teams	Group
4	Workbook answers	Homework	Team 3 & 4	Group
5	Optional class assignment	End of term homework	Team 3 & 4	Group
6	Post-intervention Interview: a. “What are models” questions	Out of class Postest	14	Individual
	b. Post-intervention Interview: “Newton’s Laws” question	"	"	"
7	a. Conceptual knowledge of forces (abridged FCI)	In class (14 sections) Postest	284 students	Individual
	b. open-ended question FCI Question 21	In class	284	Individual
8	Formal reasoning (ATFR)	In class	77	Individual
9	Document literacy	"	315	Individual
10	High school and College grades	N/A	284	"

3.5 Data analysis procedure

Needless to say, the data analysis techniques used span a wide range of theoretical paradigms. From quantitative analyses (e.g., MANOVA; more on this in Volume II) for large data sets, to a variety of qualitative analytic techniques (e.g., emergent coding, conversation analysis) for the corpus of ethnographic data. Our case study analysis is informed by ethnomethodological approaches (Garfinkel, 1967), and our unit of analysis is the group as a whole. Specifically we conducted *discourse analysis* (e.g., Garfinkel & Sacks, 1970) on the full transcripts and applied more fine-grained techniques (e.g., ten Have, 1999) to small segments.

While methods such as MANOVA are ubiquitous and well understood in social science research, qualitative techniques such as those used in discourse analysis, and other forms of ethnomethodology, are less well so. Briefly, these methodologies start with the assumption that all human interaction involves acts of sense making. Thus, ethnomethodology seeks to describe the underlying interactional rules, procedures, norms and practices (i.e., *methods*) people come to use as part of the processes of social organization. In doing so, such analysis consists of attempting to understand the actions, mutual knowledge – i.e., common ground – and social context that are created. On a practical level, this form of analysis involves the close observation of video or transcripts with an eye to understanding the methods people use to make sense. It consist of analyzing the back and forth transactions humans engage in as they attempt to understand and clarify their understanding – i.e., conversational turns and conversational repairs, or what Clark and Schafer (1998) refer to as *contribution to discourse*. What such analyses tells us are the fine-grained and the subtle things we do to understand each other and construct knowledge. It shows us what we take for granted, i.e., the things we no longer as to be justified, "taken-as-shared" (Cobb, 2002). It shows us how these common understandings come about, or fail to come about. We refer our readers to Schegloff (1991) and Clark and Brennan (1991) for a good overview of these methods. We continue with this elaboration next.

3.5.1 Overview of Procedure

Qualitative analyses use somewhat different methods to get at the heart of the processes involved in performance of tasks and participation in the collective activity. One of these methods is to analyze the discourse and actions of individuals as they attempt to make sense of each other's engagement during the performance of "naturally occurring" activities (e.g., discourse analysis, conversation analysis, interactional analysis). Generally speaking, these methods come to involve the study of social interactions and issues such as authority and status (i.e., social positioning). Conducting a discourse analysis is an assembly of interspersed episodes that must be woven together to make sense. Because conversations are seldom linear or complete in themselves, one relies on specific segments of the data to reveal certain patterns of sense-making between participants. From these, conjectures or hypotheses about these patterns can be developed and tested on other segments from the data corpus (see Cobb (2002) for an example of this technique). Such analysis helped him uncover the overall goals of the episode as co-constituted by the participants. Ultimately, as educational researchers and designers, we can use this knowledge to determine how closely the normative purpose matches the intended purpose of the instructional design.

How do we develop the unit of analysis? In social settings people participate in conversation as part of social activity including planning, discussing, negotiating, and convincing. They do so as collective actions, structured in a highly coordinated dance based on social norms and rules, which Clarke and Schaefer (1989) refer to as *contribution* to the discourse. For instance, the initiating speaker attempts to ensure that her presentation (sub-contribution) is being attended to, though evidence provided from the other participants (acceptance). This evidence comes in the form of acknowledgement that she is being heard first and foremost, and then, that she is being understood. In other words, participants are mutually dependent on each other in this coordinated activity through the process of recursive feedback loops that ensure the larger contribution is understood. This unit of analysis is a useful one when studying social actions. Let us elaborate further.

> When people participate in a discourse, they generally try to make a success of it. According to most theories, all they have to do to achieve success is utter the right sentence at the right time. But this leaves too much to chance. Was the utterance heard correctly? Was it interpreted correctly? Do all the participants believe it was interpreted correctly? In actual conversations, we have argued people hold out for a higher criterion. They try to ground what is said – to reach the mutual belief that what the speaker meant has been understood by everyone well enough for current purposes. In doing this, they create units of discourse call contributions.
>
> Clark & Schaefer, 1989 (p. 290)

Contributions are made up of different types of utterances that might be considered as falling into two phases: (1) presentation phase, and (2) acceptance phase. Presentations are utterances that are offered up for consideration as sub-contributions. Acceptances are utterances that demonstrate if the partner understands the presentation through some type of evidence (see Table 4 for examples). The acceptance is a recursive action, which only stops once the contribution is finally completed. Such termination is only determined post hoc. Contributions can be in the form of full utterances (sentences) or elliptical ones. Contributions are used to ask questions, make assertions, make requests, and/or make promises. These are considered *illocutionary acts* (Austin, 1962). Contributions are composed of presentations and acceptance phases. A contribution can hierarchical and be made up of several instalments or sub-contributions.

Collaborative completions are jointly constituted contributions. The presented contribution is accepted by the partner by being completed, hence, setting up another contribution which may or may not be accepted. Clark and Schaefer (1989) suggest that generally there are five steps in this contribution cycle.

Table 4. Forms of presentations and acceptance utterances. Adapted from Clark & Schaefer, 1989.

Presentation of Utterances	Acceptance of Evidence
Acknowledgement	Continued attention
Completed turn	Initiation of next relevant turn
Portion of continuing turn	Acknowledgement, often overlapping
Instalment of extended turn	Acknowledgement during pause
Instalment for rote memory	Verbatim display
Trail constituent	Explicit answer
Incomplete utterance	Completion
Completion	Repeat plus assent

RESULTS

Before reporting on our main results we start with a general description of the four teams. In doing so, we hope to provide a context to explain the factors influencing development and learning: (1) the cognitive resources available to the teams (i.e., prior learning and experiences); (2) their development of social positioning and willingness to participate collaboratively; (3) their willingness to take action (i.e., sense of agency) and sense of belonging (i.e., identity).

4.1 Case Reports

Recall that the case study research was composed of 16 students from two distinct populations of first year science students. In the preparatory grouping we had Teams 1 and 5[8] while in the honours grouping we had Teams 2, 3, and 4. To provide an adequate context for the case study results we will start with case reports on four of the teams, including a brief description of the students as well as summaries of the three main activities that made up the intervention: (1) *building cars activities* (physical models), (2) *working on the model-bridging storyboard* (bridging between physical and abstract models), and (3) *working with the SIMCARS* simulation (computer model). Note that the length of the case reports directly relates to the roles played by those teams in allowing us to answer our research questions. Thus, Teams 1, 3 and 4 are featured in more detail, while Team 2 and 5 are not.

4.1.1 Team 1 Case Report

Team 1 was originally composed of five students (Malini, Francesca, Batuk, Mike and Nazir). We only describe the four DSP students[9], Malini, Francesca, Batuk and Mike (2 female and 2 males, respectively). These four students were seventeen years old and all had graduated

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[8] Note that Team 5 had problems with their scheduling and we did not collect complete data on their activities.

[9] Nazir, an NYA student, was originally part of this group, but after the first session we realized that his placement in this group was counter productive. He clearly his profile was not well represented by the entry assessment measures. We reassigned him to Team 4 and will describe his prior experiences there. Additionally, Mike later dropped out of the research project after session three. He did not tell us the reasons, though others in the team suggested that it was a scheduling problem and not a lack of interest.

from high schools in Montreal. Malini, Francesca and Mike had completed high school in English, though it was possible that English was not their first language. Batuk, had immigrated to Canada as a young adult and identified his first language as "other," i.e., not-English and not-French. They had all taken some science in high school. Malini and Francesca had taken and done well in Physical Science 416 (grades 94 & 89, respectively); whereas, Batuk had taken and just passed a higher level Physical Science 436 (grade 68). Though they had all taken math, Malini had taken and just passed 4th year Algebra (Math 436) (grade 62), while Francesca and Batuk had taken and just passed 5th year Functions (Math 536) (grades 67 & 63, respectively). We do not have complete data on Mike.

Looking at other cognitive capabilities assessment measures, the Nelson Denny Reading Test showed that the two girls were average to low in regard to vocabulary and comprehension: Malini's scores were 39 and 36, respectively; and Francesca's scores were 30 and 32, respectively. Malini's score, though low, is considered within the range of average, which means she was placed in the Introduction to College English level. Meanwhile, Francesca's scores placed her in the introductory course that is intended to provide low scoring students with extra support and guidance with English. We did not receive Nelson Denny scores for Batuk or Mike, however, they were both placed in the Introduction to College English level, which means that they were both evaluated as being above the threshold for vocabulary and comprehension.

The scientific interests of these four students included such topics as biology, chemistry, astronomy, and marine biology respectively. All four students reported that they sometimes watched science programs, Batuk and Mike reported that they sometimes read science magazine. Batuk and Mike reported that they had prior experience with games or simulations that could be related to science. Mike qualified by saying "not any more." Then later on added: "as a kid I had many science/math based computer games. I also learned how mechanics work by building toys and Legos, and using other electronics in the lab."

Malini, Batuk and Mike reported that they had participated in science fair competitions, Batuk's single experience was in regard to "investigating how pulleys work." Malini and Mike both had multiple experiences with science fairs at high school. On one occasion Malini project was to examine the phenomenon of *biophelia*[10] and on the other she examined the operation of pinhole cameras. She claimed that these taught her to "organize data." Mike's science fair experiences included investigations of coral reef deterioration and seemed to relate to his interest in scuba diving. He was awarded second prize for one of these projects, at the local level.

What we learn about these students from these profiles is that they were similar in their weaker math abilities, and possibly in their language vocabulary and comprehension. In regard to their physics prior knowledge, we see that while the two girls had done well in Physical Science 416, they had not taken level 436, which suggests that they didn't have the necessary depth of knowledge coming into Cégep science. Meanwhile, Batuk's grades for the Physical Science 436 were low. All these factors contributed to their placement in preparatory science. What was notable, however, was that three of the four had an extra curricula interest in science, which might explain their willingness to participate in this research project and could have been well positioned to benefit from the environment we set up in the research intervention. We turn next to a brief summary of what happened.

Summary of their building activities. Overall, the four students seemed enthusiastic about learning science and willing to participate in an extra-curricula activity – there was also the possible reward of getting bonus marks for their physics course – yet they had a slow start with the building activities. To start, Mike arrived late (as did Nazir who was later in session 2 was reassigned). While waiting, Francesca was selected to be the group's information person. By this we mean, she was the one reading the instructions from the workbook, though each student had their own close at hand.

What we also noticed was that in reading the instructions out loud, Francesca did not read through the instructions but stopped once she thought she'd read what was necessary to get started. In doing so, the group had an incomplete understanding of what was required and didn't move forward with their task yet seemed content to remain stuck. To top it off, the four students did not demand more, nor did they seek out help, though several researchers and the two

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[10] The term "biophilia" literally means "love of life or living systems." It was first used by Erich Fromm (1964) to describe a psychological orientation of being attracted to all that is alive and vital. The biophilia hypothesis suggests that there is an instinctive bond between humans beings and other living systems. Edward O. Wilson (1984) introduced and popularized the hypothesis in his book entitled Biophilia.

assistants were within earshot. As a result, the group appeared to have mixed understandings of the instructions, hampered their joint planning and development of joint problem solving strategies.

Still in the first session, it also seemed that different members of the team had different ideas about the task's objectives. For Mike, it was all about designing the best car, while for Batuk (and later Nazir), it was partly about designing an experiment. When it was brought to the group's attention that designing an experiment was the goal, the team struggled (except of Nazir). They didn't know where to start and had problems designing ways to control for experimental error. What might be easy in a recipe-type lab experiment is not so in the real world of messy variables.

When it came to using physics, the group struggled (with the exception of Nazir). They tried to recall what their teacher had said in physics class, in doing so, attempted to apply this knowledge without consideration of the phenomena generated by the activity. Later, we will show examples from their actual transcripts.

In the two other building sessions, the team, Malini, Francesca, Batuk and Mike, began to engage in joint planning and decision making, which seemed to promote development of a sense of shared enterprise and common knowledge. However, they continued to be slow at taking up such actions as trouble shooting and correcting factors affecting their car's performance. To do so, we believe, requires a sense of agency. But, in the meantime, what we noticed was that the students relied on the researchers' noticing their need for help and subsequent scaffolding of their reasoning by the researchers.

In regard to physics knowledge, the group continued to directly apply their classroom experiences, without consideration of the activity or the phenomena produced. That said, on many occasions, as individuals, they each would make relevant observations but these would not be followed up. Either the observation was overlooked by others, or the attempt to explain with science was dropped when it got hard.

In summary, thought the students in this team seemed willing to participate and returned each week, they weren't accustom to having the authority to make decisions and to set their own goals and standards. Additionally, they weren't accustom to taking personal responsibility or taking self initiated actions that could result in their own learning, i.e., recognizing the need to know, persisting with activity that required cognitive effort and using resources to help puzzle through a challenging problem.

Working with the model-bridging storyboard. For Team 1, working with the model-bridging storyboard involved a moderate degree of coordinated activity among the four students. With the exception of Mike, they all seemed genuinely interested in completing the storyboard. We can't tell for sure, but Mike seemed to have little use for this tool and took himself out of the action, though from time to time he offered up useful insights. In general, using the model-bridging tool helped to focus the students' discourse on the issues of physics. In fact, they collectively raised good questions and problematized the activities involved, which in turn, could lead to further discussion. However, they continued to have little confidence in their ability to answer their self-generated questions. And, unfortunately, this episode of self-directed learning was thwarted by a somewhat jealous attempt to scaffold the students' content knowledge. In short, we offered too much help. With a seeming authority figure, the group reverted to shallow forms of talk that we see when students answer class room questions – i.e., they go on a fishing expedition, trying to guess what the right answer might be, "is it?"

Summarizing working with SIMCARS. Working with the simulation was probably the most successful activity for this group. By then there were three, Francesca, Malini and Batuk. Finally they were all on an equal footing, though Batuk and Malini were clearly the ones who raised many of the questions and seemed to enjoy debating each other. They all demonstrated a greater sense of confidence and willingness to discuss the science. They also were intrigued by the differences between the simulation and their real experiences and much of their discussion focused on the understanding of models and their use in science.

In the final joint debriefing sessions (both Team 1 & the unreported Team 5) that followed these activities, Team 1 was animated and had little trouble presenting their ideas and supporting their conclusions. All three students, but particularly Malini and Batuk, seemed to have developed a sense of agency and willingness to present and defend their understanding of the activities as well as the physics. Later we will present some of their thoughts related to such developments.

4.1.2 Team 2 Case Report

Team 2 was composed of four honours students, Brigitte, Betty, Winona and Coby (3 females and 1 male). Brigitte, Betty and Coby were eighteen, and Winona was seventeen. Betty and Winona had attended high school in English, while the other two had attended high school in French – Brigitte's high school was in a small town outside of Montreal. It was obvious that Brigitte was French speaking, but not so for Coby. All four students had taken science in high school and had done well. They had all written Physical Science 416 and 436, and Physics 534: and, on average, they had scored above 85: Brigitte (92, 87, 87), Betty (89, 74, 90), Winona (92, 86, 83), and Coby (99, 98, 97). The same could be said about their two math courses (math 436, 536), Brigitte was somewhat weaker than the rest: Brigitte (81, 82), Betty (91, 85), Winona (96, 86), and Coby (100, 96).

When it came to their scores on the Nelson Denny English placement test, Betty (82 vocab, 60 comp) and Coby (62 vocab, 64 comp) were well above the other two – Winona (48 vocab, 44 comp) and Brigitte (23 vocab, 20 comp). Brigitte's low score meant that was in the preparatory English course, while the other three were assigned to Introduction to College English.

Surprisingly, as a group these students reported lower interest in science extra-curricular activities. Only Winona claimed that she sometimes read science magazines. When it came to science programs, Winona and Betty stated that they sometimes watched Discovery channel, their main interest being animal behavior and environmental issues. None of these four had ever played scientific games or simulations. Only Coby and Winona had experience with projects such as science fairs. Coby had done a project investigating gravitational forces, Winona had participated in several projects: destruction of the Amazon rain forest, how meat and dairy affects the level of acidity, which in turn might affect the development of ulcers. She claimed that the experience helped her learn how to collect and analyze data.

In summary, these students appeared to be equally prepared when it came to their knowledge of physics, and somewhat less so in regard to their math capabilities. Brigitte had slightly lower scores in math, and much lower scores on the Nelson Denny. When it came to their experiences, Winona and Coby had more experiences with extra-curricula science. This should have set them up with greater competence, and possibly more willingness to participate, when it came to working with models. What happened, however, is described below.

Summary of their building activities. For some reason this team engaged in more socializing than the others. Though Brigitte seemingly wanted to use this opportunity to improve her physics understanding, Betty, the more competent of the two, seemed jaded and did not make such efforts. This group appeared to assign themselves specific roles, the girls worked on answering the questions while the lone male, Coby, seemed to do most of the tinkering and troubleshooting. The girls seemed to emphasize the outcome criteria (i.e., the furthest performance), less so the physics. Meanwhile, Coby emphasized the process. They introduced personal experiences and used the car building time for social bonding. When the girls experienced technical difficulties they were easily frustrated and did not try to isolate problems. Instead, they looked to other groups for solutions – e.g., how to position the balloons on the car to make it go forward. Though sometimes they were the source of ideas – e.g., where not to place the start line. Meanwhile, Coby, the lone male, was responsible for all the team's troubleshooting and general debugging of problems – e.g., finding a way to stabilize a wobbly wheel. Those activities provided him with more opportunities to talk science, which he did with his male counterparts, particularly those in Team 4.

Disappointingly, the team, particularly the girls, performed these tasks as though they were items to be checked off a homework list and not as opportunities to discuss science. Such actions are typical of "compliant" participation practices (Schwartz, 1999).

Summarizing working with the model-bridging storyboard. For Team 2, working with the model-bridging storyboard involved little coordinated action between the four students. To start, this team spent the least time working on the storyboard because they ran over time completing their testing of the car. Once started, Brigitte took on the role of "scribe" (in this case secretary might be more accurate) and seemed genuinely interested in completing it. Meanwhile, the others acted more like spectators answering her questions as though participating in a fill-in-the-blank exercise. This style of questioning elicited mere factual information rather than evoking deep physics reasoning. Thus the storyboard did not produce any robust discourse episodes. In the one valid instance of potential discourse, Coby was responsible for providing the answer to the question but he did so in a manner that put a stop to further discussion. The others deferred to him because they seemingly believed he possessed greater intellectual prowess to him.

Summarizing working with SIMCARS. Again the team did not take the activity seriously. Though they engaged in trying out different aspects of the simulation, they choose to discuss personal issues and generally socializing with others in the class.

In summation, Team 2 took the entire experience less seriously than did the other teams. In doing so, they let most of the affordances for learning slip by. This proved an unfortunate lost opportunity for Brigitte and Winona, both of whom we will show did not do particularly well in the other assessments of physics concepts (namely the FCI). Though we draw no causality, we point to students with lower starting grades – e.g., Malini – who participated fully and also considerably improved their showing on the FCI.

4.1.3 Team 3 Case Report

Team 3 was composed of three honours students, Gilles, Ray and Floyd (all males). Gilles and Ray were seventeen (Ray turn seventeen just before the start of the instruction and Gilles just at the end of the instruction), while Floyd was eighteen. Gilles had attended a French high school and English was clearly his second language. Both Ray and Floyd had attended English high schools. All three had taken science in high school and had done very well. In fact, they had all taken physics and had written exams for Physical Science 416, 436 and Physics 534. Their marks were consistently high: Gilles (100, 96, 99), Ray (95, 85, 97), and Floyd (97, 92, 91). Additionally, they had all taken Chemistry 534, also with high grades (98, 97, 92, respectively). And, they had all taken and done well in both Math 436 and Math 536: Gilles (100, 98), Ray (95, 92), and Floyd (92,88).

When it came to language skills, surprisingly, Gilles scored high (58 vocab, 58 comp) on the Nelson Denny though he was a second-language speaker. Floyd too, scored very high (78 vocab, 64 comp), while Ray was considerably lower (48 vocab, 44 comp). All three qualified for the Introduction to College English courses. When it came to scientific interests, all three reported that they read science magazines from time to time, their interest ranged from modern physics to chemistry. They all answered that they often watched science programs on TV, indicating that they particularly liked shows relating to physics and math. Ray specifically listed shows such as “Bill Nye the science guy”, “NOVA”, and so on. When it came to games or simulations, only Gilles had prior experience with these diversions, and reported that what he’d really meant was that he was trying to create racing software that incorporated the physics he’d learned. Interestingly, only Gilles had previous experience with extra-curricula science fair projects; his investigations included projects involving airplanes, propulsion systems and topics in chemistry. When asked, he claimed that these experiences taught him about preparing experiments, but mostly what was learned “was not really tangible.”

In sum, compared to the previously described teams, Team 3 was pretty homogenous. This was an all male group, made up of three good science students. They had all obtained high grades in their science and math courses. Seemingly, there were few differences between them except for Floyd’s age (one year older) and Ray’s lower Nelson Denny score. These differences, though small, may help explain the jockeying of social positioning during their activities, which we describe next.

Summary of building activities. From the start, session 1, Team 3 (Floyd, Gilles and Ray) demonstrated good organizational skills. Their efforts were coordinated but they maintained a certain level of independence with each member taking on specific concerns. For instance, Floyd might go off to weight the wheels, seemingly socializing, but would return with important information to share. Such actions suggest that the group shared common goals and also shared a sense of responsibility for adding to the collective knowledge of the group – i.e., common ground. It seems like a certain amount of division of labour is possible when group members share common goals and intentions.

With each successive session, these three students continued to approach their car building in an organized and systematic fashion. They anticipated features, other than the independent variable, that might influence their data collection, e.g., changes to the weight of the car. In short, they displayed a high degree of planning. They also spent a lot of time debugging problems with the car, when it did not move forward or go straight. They discussed reasons for the car being “stuck” and solutions to get it “unstuck,” e.g., raise balloons so they don’t touch the wheels. They easily used physics to predict the performance of their car and again to explain changes in results – e.g., changes in the elasticity of the balloons affecting the amount of force produced between the first trial and the forth trail. When their predictions did not pan out – e.g., three balloon engines did not go as far as two balloon engines – they were intrigued and examined the phenomenon. In fact, the anomaly generated much attention and discussion of the physics involved, albeit, phrased in somewhat lay terms – i.e., a combination of factors relating to weight and drag.

Working with the model-bridging storyboard. As with other activities, Team 3 was capable of engaging in this task and making sense of the physics involved, though there were some issues about the way they approached the model-bridging storyboard; more on that later. What was important in this instances was how working with the model-bridging storyboard revealed social issues between the team members that might have influenced collaborative learning. While there appeared to be equal sharing of tasks and leadership roles among Gilles and Floyd, Ray was left out. At first it seemed by his choice, but later there was a sense that Gilles and Floyd had positioned him as less relevant to the team's decision making. Thus, when Ray raised some concerns about how to interpret the forces represented in the chapters of the storyboard, his contribution was rejected. And, though he failed to make his point, by dismissing his concerns, the others missed an opportunity to go deeper into their own understanding of the topic.

Summary of working with SIMCARS. Team 3 worked seamlessly with the SIMCARS simulation. They immediately got to work and understood that the purpose of the activity was to examine Newton's Laws under controlled and ideal conditions. They contrasted this with the clumsiness of their real life experiments, particularly the anomalous data generated by the three balloon engine. With these contrasting cases they discussed what they had learned from the experience with both types of models and the benefit of having done both.

In summation, Team 3 was an example of a homogenous group. For the most part they worked efficiently and systematically. Though they appeared to easily engage in joint planning, problem solving, and trouble shooting, clearly there were some social issues underlying their joint participation. We believe these may have influenced and diminished the potential of their joint accomplishments. We will use this as a point of analysis later on.

4.1.4 Team 4 Case Report

Team 4 was composed of three students (all male), Tarun and Frank from the honours science and eventually Nazir from regular science program. Tarun and Frank were seventeen years old. Nazir was eighteen and had taken a year off before continuing on to Cégep. Among these three, only Frank had attended English high school. The other two had attended French high schools, but their mother tongue, respectively, was identified as “other.” All three students had taken science in high school, but we do not have records for Nazir. Transcripts for Tarun and Frank show that they did very well in their Physical Science 416 and 436, and Physics 534: Tarun (99, 96, 93) and Frank (97, 96, 85), as well as their math courses (math 436, 536): Tarun (98, 99) and Frank (93, 85). When it came to their language placement, surprisingly, Tarun (64 vocab, 58 comp) did better than Frank (47 vocab, 20 comp) although he was not schooled in English. And, interestingly, Nazir did very poorly in the vocabulary portion of the Nelson Denny test (17 vocab, 32 comp). As a consequence Nazir was assigned to preparatory English, while Tarun and Frank were enrolled in Introduction to College English.

When it came to their interest in science, Tarun and Nazir reported that they sometimes read science magazines with an interest in topics, such as, health, medicine, and astrophysics. They reported that they watched science programming on TV, these included documentaries on physics and chemistry. None of the three had ever played with scientific games or simulations and only Frank had entered a science fair: his project on bacteria on cutting boards had won a gold medal. Like others who answered this question in the affirmative, Frank claimed that the experience taught him how to perform very careful experiments and collect data, and how to write scientific reports.

In summary, this group was well matched in every way except in the Nelson Denny scores. In this instance, however, these differences did not make the same impact as with other groups. As we will show next, this group was probably the most egalitarian and supportive of each other’s positional identity.

Summary of building activities. Team 4 was made up of only two students, Frank and Tarun, in session 1. They set to work immediately and from their discussions it appeared that they shared common goals and a high degree of common knowledge. Each was comfortable making decisions and each seemed comfortable explaining their actions or contributing to a shared idea. When it came to running experiments, they had no difficulty controlling their variables or applying physics concepts to explain the workings of their car.

In later sessions, when Nazir joined their team, the three students continued to work in a jointly shared fashion and acted with seemingly common goals. They each assumed a different role, though they all equally participated. They were skilled at sharing their planning, their problem solving and their use of scientific reasoning to justify their decisions. They were also good at trouble shooting and debugging problems with their car's performance. All these skills lead to a smooth running team.

Working with the model-bridging storyboard. For Team 4, working with the model-bridging storyboard involved a coordinated action between the three. Their organization of the tasks and self-assignment of roles was nearly instantaneous. While Tarun immediately assumed the role of "scribe," the others took on different complementary roles, Frank providing the big picture ideas and Nazir filling in details. They took a strategic approach to the storyboard, organizing it from the perspective of the most important concept, the free body diagram of forces. Working with the storyboard generated lots of questions, which promoted lots of elaboration and easy flowing use of physics. Overall, their discourse pattern was cyclical, first identifying and naming the large concepts, followed by more specific definitions and conditions under which it applied, or did not apply.

Summary of working with SIMCARS. Like their peers in Team 3, this group of students also understood the purpose of working with the simulation. They discussed the difference between it and real life and experimented with the different propulsion forces, however, being located next to Team 2, they did do more socializing than Team 3. Nonetheless, their discourse was about differences between models and simulations.

In sum, these three students used the model-bridging activity to engage in productive use of physics discourse. Throughout, their conversation remained deep and robust because of the problematizing style of talk. But more importantly they respected each other, which maintained equal positional identities.

Summary

All four teams also appeared to have some degree of success using the different types of models and achieving joint accomplishments (e.g., the data and the science discourse). In the case reports we demonstrated that success and achievements were differentially distributed between the teams for a variety of cognitive and socio-cultural reasons. In our efforts to answer our research questions relating to acting on the affordances for learning with models made possible through collaborative activity, and the model-bridging tools, for this report we will focus only on a couple of the teams and highlight a few of the successful instances, and less successful ones. In doing so, we reveal more about what mediates such participation and lead to these groups using models and reasoning about physics collaboratively.

4.2 Case Study Analysis – Reasoning With Model-Bridging Tools

Turning next to the general uptake of the affordances for learning that are embedded in the many modeling and joint activities with the representation transformative tools. We noted many differences between the teams and how they took up learning opportunities, or did not. Clearly, these tacit decisions influenced their levels of productivity and what we are describing as success. In almost all cases we believe these differences involve both cognitive and social capabilities and practices that relate to problem solving. We will focus here on how the model-bridging tool was used, but refer the reader to the appendix for some examples of the transcripts and logs (see Appendix I).

The episodes presented are composed of the contributions made by students in the respective teams. We have divided the full episode into sub-episodes, which represent several contributions (Clark & Schaefer, 1989). Recall that this unit of analysis is constructed when two or more individuals sustain a single focus and in doing so come to share understanding of definitions, procedures, what’s to be considered relevant and so on. The analysis of contributions allows us to capture how individuals interactionally establish their goals and come to construct the common ground and norms that they take for granted. In doing so, we can better understand what is meaningful to individuals as well as how they choose to jointly make meaning of the events (context) they find themselves in.

Only two teams, Teams 3 and 4, could be described as truly using the full potential of the model-bridging storyboard, however, at least three (Team 1 included) attempted to taking up the affordances for reasoning and learning with it. We focus on Team 3 and 4 and attempt to explain the mechanisms that promoted this type of productive participation by team members, but we also show the efforts of Team 1. Additionally, while both Teams 3 and 4 were productive, one functioned better than the next. We use these as *cross case comparisons* (Merriam, 1998) to further unpack the socio-cultural factors at work – we believe these may indeed account for instances of more robust reasoning opportunities. As such we start with Team 3, then contrast Team 4's participation with their, and conclude with a brief view of Team 1.

4.2.1 Team 3's Experience With the Model-Bridging Tool

Overall, this episode features three students, Ray, Gilles, and Floyd, working side-by-side with the model-bridging storyboard situated between them. From their actions, it is clear that Gilles and Floyd have taken on the roles of major contributors, while Ray has taken a backseat. His demeanour and handling of the physical model (shuffling the car back and forth) suggests a level of discomfort and distraction, which may be related to his feelings of being marginalized, perhaps. In the sub-episodes presented we show how the use of the model-bridging tool mediates Ray's role and how he attempts to change his *social positioning* through his interactions with it.

The segment below starts with Gilles and Floyd as they struggle to make sense of the storyboard, specifically what aspect of the representation they should start with (the pictorial or the acceleration dot drawings). They go back and forth between each attempting to hand off the drawing task to the other, all the while ignoring Ray. Deciding that the drawing is not the forté of either they move on the more scientific and more familiar representation of acceleration dots.

01 Floyd: OK (same time as Gilles). Yeah, why don't we, we skip that one (points to next line). OK, dots!
02 Gilles: dots! (same time as Floyd).
03 Floyd: OK, so at the start it's speeding up so the distance between the dots is getting bigger (points).
04 Ray: yeah.
05 Gilles: oh! You mean just draw dots.
06 Floyd: yeah, you have to draw a dot diagram. (Starts drawing). Like this.

07 Gilles: yeah, yeah, yeah, I just get it. It's speeding up so let's say this, then ... (drawing)
08 Floyd: bit further, (gestures a waving in direction of the movement).
09 Gilles: further, and. Oh! Yeah, you're right! (erases). You have to.
10 Floyd: it's speeding up, it's speeding up (moves to an upright position).
11 Gilles: mais (but), it's just like.
12 Floyd: No, it's going the other way (points to the left and then returns to the bent over position). (laughs).

In this instance, Floyd is the initiator and regulates the flow of information within the group. His first statement (line 01) reveals that he has a clear understanding of the task at hand and what positioning dots represent vis á vis motion (i.e., speeding up is represented by dots moving further apart, slowing down the opposite). Ray's yeah (line 04), and Gilles' (line 13), clarification, are ambiguous but suggest uncertainty on their part. Gilles' statement – "oh! You mean just draw dots" – is important as it indicates that, at that instance, he finally got it. He'd begun to understand the demands of the task, but it does not confirm that he fully understands the relationship being represented by the spacing of the dots. Floyd doesn't just confirm this apparent understanding, but takes no chances and shows Gilles what he intends – "like this" (line 06). Gilles' next contribution (line 07), confirms that he understanding, which allows him and Floyd to build upon their now common ground. In fact, they no longer use full phrases to discuss their thinking but allow the tool and the drawing affordances to mediate their thinking about the relationship between acceleration dots and the actual phenomenon they observed with the car's motion. "It's speeding up so let's say this..."

As the conversation proceeds, Gilles takes over the lead with an interactional move considered to be an act of *problematizing* (Greeno, 2005). At this point he appears to understand the purpose and procedure of constructing the representation but he is confused by what might be considered a subtlety (line 25), the transition point between no motion and motion at the position of "start." This is not an arbitrary question. As we will show later, such questions, focusing on change of motion or more generally phase-shifts, appear to take centre stage when certain students engaged with this model-bridging tool. This was an affordance of the tool, and these students had taken the opportunity to use it. In doing so, they could reveal both correct conceptions as well as misconceptions.

13 Gilles: I'm sure at start it's not moving. (points) That one's speeding up.
14 Floyd: oh.
15 Gilles: (scratches his head) ok, (bends over again and starts drawing) so let's just consider we move this here (stands upright and gestures).
16 Floyd: ha, ha (laughs)
17 Gilles: See. (bends back down and returns to drawing) But what it starts then? What is start, if it doesn't move at start? (stands upright and directs the question to Floyd).
18 Floyd: (pointing to drawing) So is that the start? But time is zero (overlapping).
19 Gilles: (same time) Time is zero.
20 Floyd: Time is zero (pointing), means there's no movement (shaking his hand while pointing), so ((it means it's not gone?)).
21 Gilles: No movement (shoulder shrug), alright (bends back down and goes back to the drawing). It's like, you would have like five dots or six points all at the same point. So you have (erases), you just don't ((?)) (laugh, then stands back up). OK, and slowing down is the exact opposite.

This sub-episode is an even better example of the affordances of this tool to promote the kinds of discourse that lead to co-constructed meaning – the back and forth contributions to shared understanding. Floyd starts by restating Gilles' question and pointing out the contradiction (line 18) – i.e., how can start be when time is zero? – and follows up with the notion that when time is zero "means there's no movement." In doing so he conveys the temporal aspect that is generally attached to the concept of motion, which allows Gilles to clarify for himself what "start" might be and how the dots represent this motion at the start and at the end (line 21).

As the group transitions from the acceleration dots representation to the free body diagram representation we see a different story emerge. Once again Gilles situates the task ahead, this time by stating it in the form of a question – "So what is this? Force... force acting on it?" In doing so, he allows the other team members to answer it thereby entering into the conversation as we will see shortly. But, one other thing is different this time, in addition, Gilles makes an overt attempt to invite Ray to participate, even if it is reasonable to interpret his invitation as a bit disingenuous[11]. And, Floyd is momentarily distracted by an announcement from the researchers. Possibly, these combined events supported Ray's sense of wanting to make his first real contribution to the joint meaning-making discourse. We will discuss this as we go

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[11] i.e., Gilles turning briefly to Ray, referring to the drawing on the motion storyboard, asks the question: "do you want to do some of this?" Ray responses by gesturing, no, you can go ahead.

along.

22 Gilles: ok, forces at the end, there's no forces except gravity.
23 Ray: No, (pointing to the cell on storyboard) forces, the natural force, the weight. The natural force goes up, (gestures with a thumb up) goes up.
24 Gilles: yeah.
25 Ray: and slowing down, there's the same natural force, weight, um, slowing down...
26 Gilles: (turning to Ray) plus friction is bigger than at the beginning.
27 Floyd: (returns his attention to the group)
28 Ray: no...
29 Gilles: so we have here, a little acceleration from the balloons
30 Ray: yeah, (pointing) and a lot greater (friction?)
31 Floyd: yeah, we have velocity that way, acceleration that way (pointing forward), and friction backwards (point backward).
32 Ray: (nods).
33 Gilles: and friction. But here friction is bigger than the balloons, and here it's opposite. Here balloons, is, bigger, than friction (said slowly as he draws it out then stands up).
34 Floyd: yeah, and you have the "g" and "b".
35 Ray: don't forget (pointing) you have the gravity and the natural force.
36 Floyd: isn't it normal?
37 Ray: yeah, normal, sorry.
38 Gilles: actually, "b" at the beginning should be the biggest. At the start the "b" force is longest (gestures).
39 Floyd: no, time is zero, so nothing's happening yet.
40 Gilles: well, it's the moment between just leaving (gestures a release motion), I think, time zero.
41 Ray: (overlapping) oh yeah, well consider that a ((?)) force (gestures a pump of the fist).
42 Gilles: just like a force is there but not, yet, movement. Like the very beginning of acceleration.
43 Floyd: oh, yeah, So there's a huge one (drawing).
44 Gilles: very huge one.

From this we see Gilles and Ray attempting to account for the forces acting on the balloon car at the end of its run (N.B., they start at the last chapter rather than at the beginning). Gilles' claim that gravity is the only force acting on the car (line 22) is incorrect, which prompts Ray to demonstrate his knowledge (line 23). With an opportunity to correct Gilles, Ray can now claim his position in the group and contribute to the common ground, but not for long. His confidence, sense of agency, persists long enough to make another contribution before Floyd returns (line 25). When Floyd re-enters the conversation he eclipses Ray, doing so by introducing an additional concept, “velocity,” which is equivalent to an intellectual “one-up-manship” and later correcting him outright (line 36). Floyd’s move may be interpreted as his attempt to re-establish the status quo social positioning.

Nonetheless, as the three engage in this discourse, they puzzle over very basic but complex physics concepts. What we note is that the model-bridging tool acts to focus the three into a common shared space. Additionally, it allows them to index the exact locations where forces change, “but here friction is bigger” and “here balloons [force] is bigger.” Such indexing allow for close observation of changes in motion, which in turn allows the individuals concerned to have such discussions as the one reported here. Such is the identification of affordances that we set out to find, and such is the uptake of affordances that we set out to examine in this research.

Moving on to another affordance, the next sub-episode shows how the model-bridging tool allowed this group (and Team 4) to begin discussing the concept of *static friction*[12]. This notion is very complex and requires a great deal of cognitive effort in reasoning through. Interestingly, both teams were willing to sustain their effort in this regard. Though these students have a certain level of content knowledge, the chapters of the storyboard and the challenges raised by Ray prompted the others to engage in reasoning that is normally not revealed. As a result, we are able to examine what these students understand about static friction closely. We

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[12] Static friction results when the surfaces of two objects are at rest relative to one another and a force exists on one of the objects to set it into motion relative to the other object. Suppose you were to push with 5-Newtons of force on a large box to move it across the floor. The box might remain in place. A static friction force exists between the surfaces of the floor and the box to prevent the box from being set into motion. The static friction force balances the force which you exert on the box such that the stationary box remains at rest. When exerting 5 Newtons of applied force on the box, the static friction force has a magnitude of 5 Newtons. Suppose that you were to push with 25 Newtons of force on the large box and the box were to still remain in place. Static friction now has a magnitude of 25 Newtons. Then suppose that you were to increase the force to 26 Newtons and the box finally *budged* from its resting position and was set into motion across the floor. The box-floor surfaces were able to provide up to 25 Newtons of static friction force to match your applied force. Yet the two surfaces were not able to provide 26 Newtons of static friction force. The amount of static friction resulting from the adhesion of any two surfaces has an upper limit. In this case, the static friction force spans the range from 0 Newtons (if there is no force upon the box) to 25 Newtons (if you push on the box with 2 5 Newtons of force). This relationship is often expressed as follows:

$$\text{Sliding } \mathbf{F}_{\mathbf{frict}} \leq \mu_{\mathbf{static}} \bullet \mathbf{F}_{\mathbf{norm}}$$

Downloaded from < http://www.gbs.glenbrook.k12.il.us/Academics/gbssci/phys/Class/newtlaws/u2l2b.html> June 22, 2007.

break this sub-episode into two parts (A & B) because of its length. We start with part A (lines 45 to 60).

45 Floyd: (talking over) oh, there's static friction stopping it from moving (turns to Gilles).
46 Gilles: yep (nods).
47 Ray: (nods) ah um. also, don't forget the static friction.
48 Gilles: so let's say it is (trailing off as he starts drawing)
49 Floyd: so it's equal.
50 Ray: ummm.
51 Floyd: (gesturing) if it's not moving then the static force, the balloons haven't overtaken it yet.
52 Gilles: yeah.
53 Ray: yes that's true because we're not talking about in motion at that time (pointing to the storyboard).
54 Floyd: so it should be exactly equal.
55 Ray: yeah.
56 Floyd: and then this one, when it stops is at kinetic friction
57 Ray: (overlapping) static and kinetic.
58 Gilles: yeah, but there's no acceleration from the balloons, so there's no. Well, there's static friction (gesturing). But there's, it's going to be in equilibrium. And it's not moving. So...
59 Floyd: it's hard to think about.
60 Gilles: it's hard to think about yeah, but. Yeah, there is friction force but it's...

In part A of the sub-episode, Floyd introduces the concept of static friction (line 45). All three students agree that it is a force to be accounted for in this scenario, but they struggle with the meaning of the concept as they attempt to represent it on the drawings. We can interpret Floyd's statement, "the static force, the balloons haven't overtaken it yet" (line 51), as meaning that static friction contains the notion of some type of threshold – i.e., the use of "yet." However, the "it" referenced in "overtaken it yet" makes the meaning somewhat ambiguous. This uncertainty crops up later on (line 54) when Floyd states "so it should be equal" we do not know what "it" refers to, and there's the rub. Does he mean that the static friction is equal to the propulsion force until the propulsion force overtakes the maximum static friction, and the object moves? Or, does he mean something less sophisticated? This uncertainty of meaning continues with Floyd's next statement (line 56) when he again refers to "when it stops is at kinetic friction." We believe he is referring to the explanation that static friction stops when kinetic friction takes over, but we cannot be sure that his team mates interpret the "it" that way. In fact, it is difficult to say from Gilles' comment (line 58) if he agrees with Floyd's definition. What is clear from this portion of the sub-episode is that both Floyd and Gilles express feelings that this is a difficult concept to think about (lines 59 & 60).

Part B (lines 61-84) continues below with Floyd trying to workout the difference between static friction and kinetic friction and how these must be represented. In doing so, he shows us another of the affordances of this model-bridging tool, it can promote scientific reasoning and argumentation. In this case, as the physical indexing of time, pointing to (line 61), mediates the individual's ability to think through the logic of other's *claim* – Ray's "no, no" (line 62). Thus we have two simultaneous processes: (1) the thinking made possible because of this temporal capture of an instant, and (2) the application and scientific reasoning and argumentation using the abstract model of motion – Newton's second law. All this is accomplished through Ray's first challenge (line 62), which prompts Floyd to explicitly define the forces acting on the object (line 64). Such discourse also occurred in Team 4, but for the moment, we will continue on with this episode B.

61 Floyd: the balloon's conked out (points to storyboard), so then there's no friction, because it's not moving.
62 Ray: no, no
63 Gilles: (looks quizzical).
64 Floyd: (stand up and counts out the factors with his fingers), there's nothing from the balloon, it's not moving forward.
65 Ray: (talking over) there's no kinetic friction but there is static friction because it's at rest.
66 Gilles: yeah,
67 Floyd: yes. (same time)
68 Gilles: but, ((whereas ?)) if we put kinetic friction there, I would be telling that this is...
69 Floyd: (talking over) If you, (gesturing toward storyboard) yeah, yeah, something has to be pushing forward.
70 Gilles: yeah, and nothing is pushing forward then.
71 Floyd: (talking over) you can't have, you can't have unbalanced, uh, frictional force.
72 Gilles: yeah, cause it would mess it up
73 Floyd: (gesturing) you can't have a frictional force without something...
74 Gilles: counterb.., qui, this thing is not moving (turning to look at Ray).
75 Ray: (looking at Floyd) yeah you can.
76 Floyd: you can't have a force pulling back on something (gesturing).
77 Ray: it's not pulling back on it, it's just, it's just maintaining it there.
78 Gilles: then which direction is it?
79 Ray: remember when we're learning it (??)

80 Floyd: but static friction works both way (gesture back and forth).
81 Ray: yeah, ok, fine.
82 Floyd: well, which way is it going?
83 Gilles: so where is it?
84 Ray: well fine, you could, you could neglect it but...

Ray's second challenge (line 65) is more elaborated and reveals his misconception, that static friction exist when an object is at rest, rather than when an object is in-between rest and motion. Gilles and Floyd appear momentarily confused as they gather their thoughts (line 66-67), then Floyd appears to reference basic physics principles (line 69), if nothing is pushing an object, there's no static friction. Following up, Floyd extends the support for his argument by again drawing on physic principles (line 71, 73, 76). His statements can be interpreted as invoking second law to explain that if there were an unbalanced static friction, the car would accelerate. Meanwhile, Gilles' comment acts to further support Floyd's explanations and echo a similar line of reasoning.

Ray's persistence (lines 75 & 77) on showing that static friction exists in the final chapter of the model-bridging storyboard reveals a deep confusion in the definition and application of the concept of static friction. He even attempts to reference the classroom authority (line 79), "remember when we learned." But, this effort does not provide him with the ammunition needed to support his claim. In the end he concedes defeat (line 81) but not a change of mind (line 84).

What in fact might be a miscommunication between Floyd and Gilles, on one hand, and Ray, on the other, plays out to be an interesting opportunity for constructing jointly shared knowledge and accumulating common ground between the students. The fact that Ray's conception of static friction seems to be confounded by notions of equilibrium would be an important outcome if this were indeed part of a physics lab. The miscommunication that began with the ambiguous "it" may be responsible because it allows the concept to remain unclear for a long time, and seemingly without resolution, at least in Ray's case.

Summary. What can we derive from this episode? To start, it shows us how this group comes to make sense of their activity. They begin by first clarifying the task to be accomplished, then proceed by constructing a joint understanding of the relationship between the representation (the acceleration dots) and the concept being represented (the 4 types of acceleration and the transitions between them). Mind you, one member, Floyd, clearly dominates the meaning-making early on as he leads the others toward a shared understanding of the task. What we also see is the affordances of the model-building tool to mediate deep discussion by freezing time and providing a way to index moments. Lastly, we see how the interactions between the model-building tool and one student's confusion, allows him as well as his team mates to closely examine a physics concept and come to a deeper, if not clearer, understanding. In the process they employ scientific argumentation methods and link abstract scientific models to the physical representations and their products.

We can also suggest that when important concepts are ill-defined they become a source of miscommunication and help to maintain misconceptions. In the next example we will show how another group handles the same concept, but with a different resolution.

4.2.2 Team 4's Experience With the Model-Bridging Tool

As before the video and transcript data from the larger model-bridging storyboard episode has been broken up into sub-episodes determined by the naturally occurring interactional frames. This episode is distinctly different from the previous team in their use of the tools and their co-construction of meaning.

As an overview, the three students (Nazir, Frank and Tarun,) worked in a genuinely collaborative and coordinated fashion, i.e., one starting an idea and another completing it. In doing so, they appeared to take on specific roles. Tarun was the "scribe[13]" who asked questions (what we refer to as problematizing). It was a job he seemed to enjoy and the others seemed content to let him take on. Nazir's role was to provide the big scientific concepts and Frank's was to elaborate and add examples.

Generally speaking, Team 4's talk consisted of statements that resembled assertions or conjectures – claims followed by response, which explained and/or more explicitly defined the concept or process being discussed – i.e., *warrants* and *backing*. But this was accomplished

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[13] The decision was made somewhere between the recording in the hallway and gathering back in the classroom. All we know for sure is that it must have been a quick and unanimous decision because the video recording was interrupted for mere seconds as the camera was relocated.

differently than in the case of Team 3.

Once the team began discussing the model-bridging storyboard no time was wasted getting to the concept of forces. They went straight to the free body diagram, bypassing the pictorial and dot modes of representing the phenomena of the balloon car. Immediately getting down to business Nazir (01) identified the forces to be considered and explained which of these were active in the first chapter – i.e., "start." Interestingly, Tarun (line 02) almost immediately introduces the concepts of static friction, which was taken up by Nazir (03) who then adds the notion of kinetic friction; and Frank who (line 04) follows up with a qualifier, adding to the team's shared knowledge of this concept.

01 Nazir: We were saying... there were four forces acting on the car, normal force….
02 Tarun: At the beginning we have normal force and weight, which are equal, right?
And we have static friction.
03 Nazir: Static friction, and then we're gonna have kinetic friction which is…
04 Frank: (overlapping talk) Only when it starts moving though.
05 Tarun: …So that overcomes static friction.
06 Nazir: So obviously the force of the wheels is bigger than static friction.

Note that in the episode above each subsequent conversational turn contributes to the accumulation of knowledge available to the team's shared knowledge – i.e., common ground. In other words, Nazir introduces the concept of four forces (line 01), starting by naming normal force to which Tarun immediately restates normal force and adds another of the forces, weight or gravity (line 02). He provides further information by stating that these two forces are equal, then adds a new contribution of yet another concept, static friction. Nazir takes up this concept and links it to the notion of kinetic friction in such a way that we might infer he views them as co-dependent or causally linked equilibrating forces (line 03). Frank confirms this definition by accepting Nazir's statement and adds more explicitness (line 04), which identifies conditions for static friction becoming kinetic friction – i.e., a transitional state or *phase shift* moment. Tarun's contribution fills in information that is missing from Frank's comment (line 05), and Nazir sums up the definition by relating it back to the car, "so the force of the wheels is bigger than static friction" (line 06).

Here we see that as Nazir comes to a conclusion, he refers back to the physical model, which acts link the physical model to the abstract notion of forces. In doing so, he reveals how the affordances of the model-building tool can be taken up and used to mediate physics reasoning.

In the next sub-episode, as the group continues to jointly constitute the meaning of the concept of static friction, a question by the researcher, pushes Nazir to think about kinetic friction (line 07). With this, the team considers the two concepts and their relationship.

07 Nazir: Kinetic friction is the, what is it, the friction that resists a moving object.

08 Frank: OK, so the object's in motion, it experiences kinetic friction if it's on a surface because the object is moving (Gestures: One hand palm up, the other moving back and forth above it)

09 Tarun: So what's static friction?

10 Frank: So static friction is when it stays still.

11 Tarun: Yeah, so what's opposing it? Getting in, into motion? Like…

12 Nazir: The molecules of, what is it, the car and the ground are too, are somehow (Gestures: Tapping the fingertips of one hand against the fingertips of the other hand)

13 Tarun: Bonding.

14 Nazir: Yeah, bonding or you know…

15 Frank: And that's where mu (gestures quotes) comes in, right? You have to overcome that mu. (moves toward the table and slides back of hand against it) Like the table is probably greater than the floor (scuffing his foot on the floor and saying something inaudible)

Frank's contribution (line 08) is accomplished through reasoning with the physical model, as well as inventing gestures to index the meaning of the motion (line 15). In doing so, he uses the phenomena observed with the physical model as a mediating device, which allows him to apply his knowledge of kinetic friction. Unlike Team 3, this group does not directly use the storyboard to locate their reasoning, instead they rely on memory and gestures of the physical model to mediate their discourse. Put another way, he uses different representational modes of expression it in such a way that Tarun can then ask for clarification by contrasting the two concepts (line 09). As the group proceeds with their conversation they get more overlap between their individual and their shared understanding. What is important in this final example is Tarun's (line 18) return to the task of understanding the motion of the balloon car and trying to understand propulsion forces. In doing so, he once again demonstrates an important contribution to the team. He is the voice of self-regulation. We continue this discussion below.

16 Tarun: ah, ok, kinetic friction?
17 Nazir: yeah.
18 Tarun: and propulsion would be, bigger? Wait, does propulsion increase over time? Or slow down? It should slow down right?
19 Frank: over time, slow down.
20 Tarun: (turns to others and stops writing, tapping on paper)
21 Frank: But it should be at it's ((longest?))
22 Nazir: no, it's increasing,
23 Tarun: yeah, that's the thing (gesturing with pencil) it's …
24 Nazir: because it's accelerating
25 Frank: it goes slow (motioning a horizontal forward movement). What was happening it was going slow, right? Then once it goes like over, once it passes like that inertia state it goes fast. It's kinda like drag (motioning up and down). Like something's in the air and it falls, it can fall slow then it accelerates like a maximum speed then it starts slowing down (moving this arm through the motion of falling from high to low).

It is this positional identity, Tarun, more so than the others, allows the group to move forward. Unlike Ray in Team 3, Tarun position is viewed positively, and he is confident in his role. Unlike Ray who makes claims, which need to be justified, Tarun proposes questions, which need to be answered. Such problematizing talk promotes deep discourse. While Ray's and Tarun's respective ways of interactions with the intervention and tools afforded group discourse, Tarun's did so in a manner that promoted more shared knowledge – i.e., greater accumulation of common ground. These examples also showed us how the models and model-bridging tool could promote and sustain discourse and conceptual understanding of abstract physics models.

Summary. What we see in this episode is the mechanisms used by this team to create a common ground to discuss and refine their understanding of the concept of static friction. Each presentation is met with acceptance and an elaboration, which makes the concept more precise (i.e., adding warrants and backing). The linguistic mechanisms used are such things as the speakers repeating parts of the previous content and concepts and using unfinished sentences that invite others in. as well, there is frequent use of words like "so" which are openings for summary statements. We might well use this as a guide to show other students how productive collaboration can be achieved.

4.2.3 Team 1's Experience With the Model-Bridging Tool

While the other two teams showed their prowess with both taking up of affordances and use of science and scientific reasoning, Team 1 showed us what is was like for the preparatory group to use the model-bridging tool. As anticipated, this case was different from the honours students. What was similar was that these students could also take up some of the affordances of the model-bridging tool and use it to help them constitute shared meanings of physics concepts.

In the first example, below, we show how Batuk (line 01) tries to explain the forces at play in the first stage of the storyboard – "start." Francesca's comment, though phrased differently, has a similar intent to Gilles' more sophisticated observation of what is happening at start.

01 Batuk: it's just two lines, weight and normal.
02 Francesca: but aren't we like keeping it from moving, so isn't it like... nevermind, it's (??) (then erases something).
03 Mike: if you leave it there, somehow it rolls forward…

What this tells us is that the model-bridging tool's afforded this particular observation and the subsequent discourse regardless of students' capabilities. What is different for these students is that they do not have the content knowledge, and if they did, it is not available at this point. Such observations have been made by numerous other researchers (e.g., Scardamalia & Bereiter, 2003). What is more interesting for our purpose is how these students tried to relate physics to the mediating tool. Unlike Teams 3 and 4, note how Batuk refers to forces as "just two lines." We show this again in the following sub-episode. We conjecture that if students only have this physical representation in mind, they are disconnected from the abstract notion. In short, lines have no direction, no magnitude, and so on, but forces do.

In the next sub-episode we show once again that the group refers to forces as static and physical things, this time, "arrows." They struggle to understand the direction and magnitude of the force, but engage in the practice of indexing the representation (arrows) to a specific part of the model-bridging storyboard. What is again different is that they do not reference the physical model. Unlike Teams 3 and 4 who work back and forth between physical model, phenomenon it produced and the abstract concepts, these students working within a flat two dimensional plane of the storyboard. In fact, only once is a reference made to the real life experience in the first half of this discourse transaction (Mike's comment in line 16), and then it has little to do with car or its performance. When eventually there is the mention of the car, it is an off hand comment, again by Mike (line 24), which is overlooked because of timing.

04 Batuk: no, the arrow is in that direction (reaches over pointing at cell on storyboard).
05 Malini: an arrow in that direction (pointing).
06 Francesca: no it's this one, this side.
07 Malini: yeah, (nods), but it's going up (pointing).
08 Batuk: but there is, but then again... (turning to Researcher 2) are we counting friction here?
09 Malini: yeah, for sure.
10 Researcher 2 (nods). What's going to stop it?
11 Batuk: friction. So there is going to be a force backwards as soon as you start.
12 Francesca: OK. (continuing on without looking up to Batuk).
13 Malini: ok, it's friction.
14 Batuk: (continues) Not as big, initially, well (looks at Researcher 2).
15 Francesca: so F,
16 Mike: the floor there is lower (for some reason?).
17 Francesca: and here is, what is this (talking in a lowered voice to Malini). What is that called?
18 Malini: I don't know.
19 Mike: what?
20 Batuk: the lines (are suppose to be equal?) (reaches over and draws on the storyboard). And this is like bigger, (takes his hand away). Whatever.
21 Mike: which force?
22 Malini: the force that this way (motions a direction).
23 Francesca: we don't even have to do this cause we have to do the net force after.
24 Mike: (at the same time) it's there, it's just the force of the balloon.
25 Researcher 2: do you know what's that called?
26 Malini: air resistance?

Lastly, we made two socially based observations: (1) the negative influence of the researcher's intervention, and (2) how easily the students gave up they cognitive effort (e.g., Francesca in lines 02 & 23). Examining the researcher's role first, we note that it was possibly responsible for the second concern, the students' giving up. However, these episodes also show that even before such outside influences, Francesca was ready to throw in the towel (line 02). Unlike Ray, she was content to be proven wrong, probably because she didn't think she had much to offer. Thus, from a social perspective, it is her own positional identity that limits her contributions. Furthermore, unlike Team 4, when another researcher asked the group a question, this team took the researcher as an authority figure, and easily gave up their authority to reason for themselves to her. Clearly, the social and psycho-social issues are much more important to the participation and learning with these learners.

Summary. Team 1 was equally willing to attempt using the model-bridging tool and, in doing so, attempted to take up its affordances for reasoning about physics. They, however, lacked some of the requisite knowledge to engage in deep conversations about the forces at play and did not use the methods that the more advanced teams used. For instance, they talked about forces as 2D entities that exist on a page as lines and arrows. They did not relate the concept, or the abstract models (i.e., laws) back to the physical models. It seems, for them, these were separate events and not merely different ways of representing the same thing. Lastly, though the students in Team 1 appeared to have equal roles, they choose to socially position themselves without authority to take action and responsibility for learning.

4.3 Working With the Physical Models

In the early part of the instruction, session 1-3, the planned learning opportunities to be taken up included understanding how to design a scientific experiment, which anticipates and controls for sources of error. It also includes opportunities for anticipating problems, trouble shooting, and relating them to physics, as well as generally applying physics knowledge in predicting the outcome of the experiments. The aim also was for students to take these opportunities to use physics.

Teams 2, 3 and 4 all demonstrated good understanding of the intended tasks and had little difficulty settling into a good rhythm of working productively on constructing their cars and their experimental design. Using the example of Team 3, we demonstrate a typical example of how this was accomplished.

In session 1, the three members of Team 3 (Floyd, Gilles and Ray) seemed to quickly establish a common understanding of the experimental design task at hand. Their actions and discourse, however, demonstrated that they had individual mental models of how to assemble the coaster car and what factors might be important in this process. In particular, when and how to apply physics explanations to their decision making.

From the discussion below we see that both Floyd and Gilles, each in their own way, appear to have a clear idea about how the wheel and axle assembly works. In the process Floyd uses physics to make and justify his decisions (line 08). He also readily identifies things he needs to complete his tasks, as he sees it, and isn't shy to ask the researchers for these resources (lines 10). From the start the three appear to be most concerned about accuracy in construction as well as advance trouble shooting by identifying sources of friction.

01 Floyd: what we have to do is tighten that (pointing to the assembly of wing nuts as they tighten the wheel onto the axle) against the wheel.
02 Gilles: yeah, I know but it's only for the... only tight enough so at least it wont... (gestures side to side wobbling).
03 Floyd: so do we want, the axle to turn the wheel? (spins the axle while holding the wing nut).
04 Gilles: yeah, yeah (overlapping)
05 Floyd: we want the wheel to turn on that (points to axle).
06 Ray: (looking on attentively, nods)
07 Gilles: no, what I mean is... or we can have a moving wheel against a fixed axle (gestures turning and opposing object).
08 Floyd: look, if you have the wood against it, I think it would be more friction, this is plastic.
09 Gilles: yeah, probably.
10 Floyd: also because this is ribbed (pointing at the treaded axle) so trying to turn that would be like trying to slow it down. (without pausing turns to researcher) Would you happen to have a wrench set? (he asks for a wrench set).

The evidence suggests members of this team have somewhat different mental models, which might explain the somewhat fragile common ground that is accumulated. For instance, Ray proposes a design solution that might provide the car with my thrust (line 11). In doing so he relates it to real life. Floyd immediately counters his recommendation using physics to refute the claim (line 15). This is a classic demonstration of scientific argumentation, a claim be refuted by scientific backing.

11 Ray: then you want to distribute the err... let's think about it (picks up the car). If you have the weight in the front, it will pull the car faster than if you have the weight in the back. If you have the weight in the back that's push.

12 Gilles: it might make it unstable, if all the weight is here.

13 Floyd: if all the weight was there means you're have weight, more fric... (interrupted)

14 Ray: no no no more here (pointing to the front axle) than there (pointing to the rear axle).

15 Floyd: yeah I know, if there's more weight there it means there's more friction on this axle.

16 Ray: yeah

17 Gilles: less in back

18 Floyd: so think of it, it's going to equal itself out.

19 Ray: but don't you know about the bobsled team. The heavier person is in the front to pull it down the slop. And since we're sliding on an incline.

Meanwhile, Team 1 showed that it was difficult for them to engage in the practice of doing science and even more difficult to link the phenomenon to science. For example, Batuk could recite second law, but there was nothing to connect this knowledge to. Thus, he and the others went around in circles trying to see how it would apply to their design.

01 Batuk: so you're saying that the weight does matter?

02 Francesca: I'm guessing, it's my hypothesis.

03 Batuk: could be since force equals mass times acceleration.

04 Malini: yeah, mass times acceleration.

05 Batuk: but then again, it well, (the kinna force equals out?) if you want more of a force?

06 Francesca: uh?

07 Malini: we wanna make it, we wanna make it...

08 Batuk: Where is this force going to? Even if, let's say the mass is greater, where is the force going to?

09 Francesca: (looking confused) force going?

10 Malini: (mumbles something while flipping through the workbook as though looking for an answer).

11 Francesca: no but it has to have some kind of friction to make it move.

Such episodes show how prior knowledge limited their possible actions. As well, note that at no time did they try to use the physical model to reason with. This is a pattern we saw again and again.

Continuing on we see another attempt to use physics. As this episode comes to a close Francesca turns to their variable. She acknowledges that they have been talking about two variables and they can only choose one. But her choice would be weight, over the circumference. Batuk tries to consol her by stating that it's "well it's kinna both, you can also see what weight does, so it's kinna both".

12 Francesca: no but it has to have some kind of friction to make it move.

13 Malini: (inserting) well force ???

14 Francesca: (continuing on) and the more it's in contact with the floor the better it is because it has more friction. And if it's lighter, you know racing cars they have bigger wheels in the back (gesturing).

15 Malini: (interrupting and directed at Francesca) but friction, wouldn't friction prevent it from moving?

16 Francesca: yeah that's why I wanna, that's why I'm not sure about that.

17 Maini: because friction, friction is, remember what he said, he said that if there's no friction, then a car will keep going and going and going (gesturing a forward motion). But there's friction (puts hand to head as she tries to remember). And did he say there would be a constant speed or something?

18 Batuk: yeah but we have to figure it out.

19 Malini: if there's

20 Batuk: but I'm guessing, like I said, if we use CD wheels there's a bigger circumference so they cover more area (rolling the CD wheel on the table). ? there's barely anything there.

21 Francesca: but wouldn't it be opposite, because like.

22 Batuk: like there's barely anything, if you look at it like this there's barely anything (picks up formcore board against CD), whereas this (picking up a wooden wheel) you would have all this (rubbing the surface of the tread) pushing backward (motioning backward).

23 Francesca: because me, what I'm thinking it should be the opposite because you need

> something to push it (?). You need, like this is probably gonna (releases the wooden wheel she is holding and rolls it forward). Yeah that is why I don't understand, whatever. We'll try and see what happens. Whatever we'll try.

It seems like the members of the group have different ideas of what the task is. But after a while it seems that they think their tasks is not the building and testing of the car but to explain "how" the variable, hypothetically, affects the car's performance.

Francesca appears to be concerned about how the thin wheel could get the job done. In obsessing about it she takes the group off track and they get caught up in a circular type conversation about the tasks and how friction might work differently when the wheels are thin and when they are thick. In doing so, she introduces ideas about racing cars and their fat tires, and compares bicycle tires to car tires, all in the aim of trying to convince her team mates that fatter tires should work better than thin ones.

After rereading the instructions in the workbook she restates her understanding of the excise and it's purpose: "it's not really how far it can go, just like you're explaining how this (pointing to the wheels) affects how far it goes. That's all we're trying to do."

While Teams 3 & 4 discuss the construction of the car and the significance of a turning wheel verses a turning axle, and the friction involved in the design, Team 1 does not discuss these components or the implicated concepts. Instead, they attend to the features of the car as design components, which prevent them from seeing any of these factors. When their CD car doesn't move, it takes them a long time before mentioning that friction is at work, instead their comments refer to over tightening of the bolts.

4.4 Analysis of Individual Understanding of Models

We analyze the results of the open-ended questions on models below. Recall that these questions were part of a written questionnaire (seen before in Appendix D.1) in the pre-intervention and delivered aurally as part of the interview in the post-intervention (seen before in Appendix E.). We also analyzed the results of the epistemology of models questionnaire (paper questionnaire), which was part of the pre and post interventions as well (see again Appendix D.1). For those results see Appendix J.

4.4.1 Open-ended questions on epistemic belief about models

We asked the students to tell us what they knew about models in both a pre-intervention open-ended question and in the post-intervention interview: (1) explain what is meant by a scientific model? (2) explain the purpose of a scientific model. Needless to say, students' responses on the post-intervention were longer, because of the oral format, but they were also considerably more detailed. Those answers included more instances of what a model is, and more elaboration on the purposes of models. Additionally, those answers included examples taken from the intervention, as well as from the students' experiences in their science classes. Because of the richness of those answers, and the blending between answers, we have developed our own methods to analyze the data.

Our analysis started with emergent coding (Strauss & Corbin, 1998) to identify more fine-grained aspects to the epistemic change (i.e., conceptual change). And, we used the classification of levels, as well as the scoring system developed by Gobert and Discenna (1997). In doing so, we identified different factors from the other work cited, we think. Such a development will allow us to conduct factor analyses at some future date to determine whether epistemic beliefs about models consist of the factors identified by Grosslight et al. 1991, or the factors that we propose here. We start with describing our emergent codes.

Categorizing students' answers. We started by examining the post-intervention answers and allowing categories within the data to emerge. Our first pass at analysis revealed five categories: *function*, *structure*, *content*, *implications of use* and *other beliefs*. With these we began to code the data, going over them in several passes, each time ensuring that the category description was a good fit, and that all the data could be placed – saturating the categories. In attempting to account for more of the data, we produced the more fine-grained characterization of the categories – i.e., the codes. For example, the category *function*, was made up of items coded as description – "models describe how something occurs" and "models help us figure out what happens" – and items coded as mechanism – "models help to explain how things work." Under structure, we coded some items as isomorphism, when it related to models as simplifications and differences of scale – "models are simplified representations" and " models are smaller representations of something bigger." This left us with notions, which seemed to be inadequately categorized, such as “models are [like] pictures in your mind” or “models make the unobservable observable.” After multiple passes and efforts to fit the data to the emergent categories, we constructed four categories – Structure, Behaviour, Function and Implications, and their respective codes (see Table 5).

Table 5. Emergent categories and codes for open-ended epistemic belief questions.

Categories	Structure	Behaviour	Function	Implications	other
Codes	Simplification	Describe purpose	Visualizations	Produces results	Feelings
	Differences of scale	Explain mechanism	Multiplicity of representations		Realizations
	Organizational levels	Dynamic in nature: runnable, testable	Conceptual representations		

We used these codes to categories the data from the post-intervention answers as well as the pre-intervention data. Once coded, we moved on to scoring these answers. For that, we turned to Gobert and Discenna’s (1997) work. In a similar study, these authors had developed nine questions to elicit students’ understanding of models and ability to use models. Two of our questions were based on their work. They scored the answers to these nine questions on a scale of 0 to 2, 0 to 3, or 0 to 4, depending on the question. We used a scale of 0 to 2, which represents the range of what is “normally” expected of students. However, we choose to score our answers somewhat differently. Instead of scoring each answer individually, we coded the entire answer because in many cases there was no separation between answers, and in other cases students repeated aspects of the answer. As such we scored the answers, as coded into the ten codes described above.

The maximum score possible for these ten codes is 20. In some rare exceptions, we believe that the scale of 0 to 2 did not accurately represent the understanding demonstrated by the students’ answer. In those occasions we gave the student 1 bonus point for the particular coded data – in effect expanding the scoring scale to 0 to 3 (same as Gobert & Discenna). These bonus points were distributed across a range of students (9 different students in all) and occurred in the following categories: *organizational level*, *explain mechanism*, *dynamic nature* and *produces results*. The results of our scoring are below (Table 6). Once scored, we sorted the scores into the four levels described below.

Table 6. Students' pre-intervention and post-intervention scores on the nine codes.

Students	Totals	
	Pre-intervention	Post-intervention
Malini	7	17
Francesca	4	12
Batuk	4	8
Betty	4	10
Coby	0	10
Winona	6	8
Brigette	4	7
Gilles	9	16
Ray	8	11
Floyd	6	18
Frank	10	13
Nazir	4	17
Sabina	8	9

Four levels of epistemic beliefs. Students' responses were coded based on a four level scale adapted from Gobert and Discenna (1997). Their scale, in turn, is based on the seminal work of Grosslight et al. (1991). We provide both descriptions of these levels. Grosslight et al.'s definitions are more stringent that Gobert and Discenna's. In fact, Gobert's (2000) more recent work, identifies intermediate levels of beliefs, which accounts for students at the high end of Levels 1 and 2. This inflates the scale to six possible levels: 0, 1, 1.5, 2. 2.5 and 3. Because we rarely see students at Level 0, we have removed this level from our reporting. In both cases the epistemic levels of understanding models are roughly as follows:

- *Level 0* = no knowledge of scientific models.
- *Level 1* = models are physical and used to visualize (Gobert & Discenna); models are thought of either toys or simple copies of reality (Grosslight, et al.)
- *Level 2* = models are representations, used to visualize, differences of scales, and to help describe (Gobert & Discenna); recognition that there is a purpose that mediates

the way a model is constructed; role of the modeler comes into play; testing of the model is thought of as tests of underlying ideas, not merely the model itself (Grosslight, et al.)

- *Level 3* = models are representations, used to explain how something works, demonstrates an idea or assist in instruction (Gobert & Discenna); three important factors come into play, (1) the model is developed to test ideas, (2) role of the modeler is to construct and evaluate which design best serves the purpose, and (3) models inform ideas by being manipulated and tested (Grosslight, et al.).

Placing students into levels was the next task. This process included consideration of the above, as well as the total score. Level 1 scores of 1 to 5; Level 1.5 scores of 6 to 8; Level 2 scores of 9 to 12; Level 2.5 scores of 13 to 15; Level 3 scores of 16 to 18.

Table 7, below, shows us that pre-intervention, five students were at Level 1, six students were at Level 1.5 and only two students were at Level 2. Post-intervention, no students were at Level 1, three were at Level 1.5, six students were at Level 2, one was at Level 2.5, and four of the fourteen students as reaching Level 3. The change was most dramatic for Nazir, with Malini and Floyd, next in line. A significant shift also occurred for Gilles, though he started with a more advanced epistemic belief. Winona was the only student who did not change level.

Table 7. Students' pre and post-intervention scores and the subsequent level of epistemic belief.

Student	Totals		Level	
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
Malini	7	17	1.5	3
Francesca	4	12	1	2
Batuk	4	8	1	1.5
Betty	4	10	1	2
Coby	0	10	1	2
Winona	6	8	1.5	1.5
Brigette	4	7	1	1.5
Gilles	9	16	2	3
Ray	8	11	1.5	2
Floyd	6	18	1.5	3
Tarun	7	10	1.5	2
Frank	10	13	2	2.5
Nazir	4	17	1	3
Sabina	8	9	1.5	2

Interpreting the results. We take Grosslight et al.'s experience as a benchmark to determine how closely our results compare. She and her colleagues looked at 33 grade 7 (mixed ability) student and 22 grade 11 (honours) students (see Table 8). Their results show that the majority of 7th graders (67%) are in Levels 1, compared to 23% of grade 11. Meanwhile, 36% of grade 11 students fell into Level 2, with only 12% of grade 7 students at this level. And, no student was categorized as reaching Level 3.

Table 8. Grosslight et al.'s (1991) results of students' placement into epistemic belief levels.

	7th grade students (mix ability)	11th grade (honours)
Level 1	67%	23%
In-between 1/2	18%	36%
Level 2	12%	36%
In-between 2/3	0%	0%
Level 3	0%	0%

When we compare our students (first year Cégep) to Grosslight and colleagues' cohort of grade 11 honours students we see that 43% are at Level 1 and 14% are at Level 2 (see Table 9). If we adjust for program and look only at the ten students in the honours science program, we see that 30% are at Level 1 and 20% are at Level 2. This adjustment brings our results closer to Grosslight and colleagues' for Level 1, though our Level 2 results remain lower. Like Grosslight, our data shows no students at Levels 2.5 or Level 3.

Table 9. Percentage of students at Levels 1 through 3 pre- and post- intervention.

	Percentage of students Pre-intervention		Percentage of students Post-intervention	
		Adjusted for program		Adjusted for program
Level 1	43%	33%	0%	0%
Level 1.5	36%	44%	21%	22%
Level 2	14%	22%	43%	44%
Level 2.5	0%	0%	7.1%	11%
Level 3	0%	0%	29%	22%

While our sample appears to have started off less knowledgeable than Grosslight and colleagues' it appears that they made considerable gains in their understanding of models and their role in science. There are several possible explanations for the differences. The most obvious is the different assessment formats – the pre-intervention was written and the post-intervention was part of an interview and aural. Though is some of the extreme cases, such as Nazir, this may be a plausible explanation, it does not fully account for all differences.

To make this judgement we turned to results of our pilot study, which was made up of 21 students (16 females and 5 males) that compare to our pre-intervention case study students. Additionally, they were similar in age and programs of study. These 21 students were given the same written questions followed by an interview, which called for elaboration. Those results show that though the length of the transcripts is longer (i.e., more was said), generally, the understanding was similar to the results we present here. In this instance, 48% were at Level 1 and 43% at Level 1.5, 19% at Level 2. No student was at Level 2.5 or above (see Appendix K). A *t-test* on these samples shows that they are statistically equivalent, p = 0.44.

4.4.2 Summary of Epistemic Belief of Models

Overall, the data from the epistemic beliefs about models questions show that our case study students, like other similar samples, started off with limited knowledge of models and how they relate to learning science. After the intervention these same students, generally, were more informed about models and were more willing to believe that models play an important part in their understanding of science, and maybe in learning as a whole. Thus, we conclude that the intervention, which included explicitly reasoning with and about models (i.e., building, using and thinking with physical models), influenced these students' understanding of models as an epistemic form.

The epistemology of models questionnaire (Appendix K already mentioned) showed us that students had problems with four items: (12) models have to be very exact, so nobody can disprove it; (13) models have to be very exact in every way except for size; (15) models have to give the correct information and showing what the object/phenomenon looks like; (16) models have to be an exact replica of the phenomenon. What these four items have in common is the notion of *isomorphism*. In the open-ended questions, this notion can be characterized by the category of Structure, with three codes: Simplification, Differences of scale and Organizational level. Comparing these three with students' awareness of isomorphism, we see that while the notion, models are simplifications, is understood by most students (57%), the two other notions are not, 36% and 21%, respectively.

Triangulation between the two assessment measures helps us better understand that, in fact, students have problems with certain aspects of this notion, namely the differences of scale, and organizational levels of models. Additionally, they have problems thinking of models as explaining the mechanism of phenomena or processes (36%), and the related aspect that models mediate between phenomena and concepts (36%). Lastly, students have difficulty thinking about models as producing results that can be used and useful in development of further models, or other scientific representations and tools (29%).

Recommendation about assessing epistemic beliefs about models. We cannot compare the questionnaire to the open-ended questions, however, we believe that the latter gives us a better general sense of what students understood about models (see summary in Table 10). Though it requires a great deal of work, we recommend that it is a better way to assess students' beliefs.

Table 10. Percentage of students coded for each of the categories and codes.

	Structure			Behaviour			Function			Imp.
	Simplification	Differences of scale	Organizational levels	Describe purpose	Explain mechanism	Dynamic in nature	Visualization	Multiplicity	Conceptual	Produces results
Percentage	57%	36%	21%	86%	36%	71%	57%	100%	36%	29%

4.5 Analysis of Individual Student Knowledge of Newton's Laws

Students who participated in the case study research wrote the FCI in their physics class, along with their classmates. We extracted those data from that corpus and analyzed them separately (NB. these students' data are also part of the larger FCI study present in Volume II). Though there is no way to make any direct correlation between the intervention and the results of the FCI, we use this smaller analysis to help us determine whether the case study students understood the concept covered in the FCI, or not. We use this information to triangulate the answers to questions about Newton's Laws that we report on afterwards.

Table 11 shows us the pretest and posttest results of 13 of the 16 students, as well as the mean scores for the program of study (i.e., honours, regular and preparatory), as well as the program standard deviation. Additionally, the table shows the Hake score (Hake 2002). Recall that the Hake score is a normalized gain score calculated to avoid the ceiling and floor effects and gives us a better description of the conceptual gain due to instruction. Hake scores >.48 are considered above average and related to interactive forms of instruction, traditional instruction provides a Hake score =.23 (Hake 1998).

Table 11. FCI pretest and postest scores for case study students by program.

Program	Students	HAKE	PRE SCORE	PRE Program MEAN	PRE Program SD	PST SCORE	PST Program MEAN	PST Program SD
Prep.	Malini	.25	30.0	21.09	13.70	47.4	28.95	14.41
	Francesca	.24	10.0	21.09	13.70	31.6	28.95	14.41
	Batuk	-.05	40.0	21.09	13.70	36.8	28.95	14.41
Honours	Betty	.25	65.0	43.00	18.20	73.7	71.16	19.02
	Coby	.82	70.0	43.00	18.20	94.7	71.16	19.02
	Winona	-.05	35.0	43.00	18.20	31.6	71.16	19.02
	Brigette	.28	20.0	43.00	18.20	42.1	71.16	19.02
	Gilles	1.00	80.0	43.00	18.20	100.0	71.16	19.02
	Ray	.76	35.0	43.00	18.20	84.2	71.16	19.02
	Frank	.18	55.0	43.00	18.20	63.2	71.16	19.02
	Tarun	.53	55.0	43.00	18.20	78.9	71.16	19.02
	Floyd	.40	30.0	43.00	18.20	57.9	71.16	19.02
Regular	Nazir	.65	55.0	31.69	16.36	84.2	44.60	20.03

What we learn from examining the Hake scores is that five of the thirteen students show changes in their conceptual understanding consistent with interactive engagement learning (Coby, Gilles, Ray, Tarun and Nazir); and Foyd's score is well above the traditional method. The low Hake scores for Malini, Francesca, Frank and Batuk surprised us given their high levels of engagement in the case study activities. Thus having other sources to help triangulate these data and tell the whole story was important. Next we look at the transcribed answers to the post-intervention interview question: How did the experience (working with cars & the computer model SIMCARS) help you build your understanding of mechanics? Elaborate on your answer and relate it to each of Newton's 3 Laws.

4.5.1 Interview Questions on Newton's Laws

We collapsed the results of this question into a single unit of analysis, which describes the student's capabilities on a five item rating scale. (1) *good to reasonable understanding* based on examples, (2) *incomplete to fragile understanding* based on examples, (3) *ambiguous understanding* based on examples, (4) *ambiguous understanding with no examples*, and (5) *misconception*. We elaborate below using the examples of answers for first law.

Good to reasonable understanding. This describes students who could correctly state the law, in their own words mainly, and could provide an appropriate example. For instance, Nazir described Newton's first law as *"[when] there's no net force on the object, and once we put the object in motion, because of its inertia, it [continues to move*]". He followed this by providing the example: "for the coaster car, the problem was [that] we had a net external force, which was the friction. If there was no friction, the car would continue on the same path, and the same speed. But, because of the friction, it stopped it." While Nazir's was probably the typical example of describing first Law, some students took the case of an object at rest as the example. Coby's answer show one of those instances:

> *"If there's no forces on an object, it doesn't accelerate. Well, from what we learned, we didn't really see any of that. Because, all we saw was forces acting on an object. Right? When no forces are acting on an object... Well, in our world, there's not much of that, really. But I guess, when a car comes to rest, you can say there's no forces acting on it anymore. Except the forces that cancel out."*

Fair to incomplete understanding. This describes students who give a short-hand definition of the law, which may omit important relationships, yet seem to understand the law based on their examples. For instance, Floyd's statement of first law is the clichéd version and does not stipulate the role of force: "*an object at rest wants to stay at rest, an object in motion wants to stay in motion*". In fact, he slipped in "outside forces act on it" in an odd way that suggests he is unclear about the role of force in first law. His example, meanwhile, explains that it is difficult to show first law in action because we are not operating in a frictionless environment:

> "*I'm not quite sure how that one works. Because it's not a frictionless environment. Yeah, but the [car] keeps rolling forward, because it wants to go forward, but friction is holding it back.*"

Ambiguous understanding. This includes students who left out necessary features of the law or who did not state the law but provided a reasonable example. For instances Ray who doesn't define the law but explains why it was difficult to show first law:

> *"Newton's first law, uh...I wouldn't say that we got to really observe that, very thoroughly, because ...we did get to see it in the sense that, um... On-, once, when we nearly had a[n] almost frictionless car, which we were trying to achieve, it should have maintained a constant speed. But with things like friction and, air resistance... we weren't able to do that."*

Meanwhile this rating also describes answers like Betty's who attempts to state first law but leaves out features like constant velocity: "*things keep moving unless there's friction*". Like others, she uses the lack of a frictionless environment as her example of first law at work, and like Coby she adds that first law is also at work when the object is at rest:

> "*when [the car] is stable, when it's not moving. There's gravity pulling on it, there's a floor, normal, pushing up. So it's not moving. It stays there*."

Ambiguous with no example understanding. This basically describes students who left out features of the law as well as provided no example. In the case of first law the descriptions all suffered from the same flaw, they used the object at rest as their example but omitted to consider when objects were moving at a constant velocity. Consider Francesca's answer:

> "*equilibrium, would probably be [an example]. When the car's at rest, all the forces are balanced. So there's no movement. No acceleration*."

Misconception. This describes when students hold false notions that probably get in the way of their understanding. For instance, Winona rightfully introduces the concept of inertia to explain first law but then she suggests that it is a state, rather than a property of an object:

> *"when, an object's in inertia, you need some force to overcome it. Like the whole balloon car, when we were at the beginning we couldn't even get it to move... it was in such a state of inertia, that our force from the balloon, couldn't propel it forward."*

Explanation of these interview results. When we look at the student's individual understanding of Newton's laws, we see that only a small handful had a good to reasonable understanding of these laws (see Table 12). To start, Nazir and Coby are the only students who fall into this category by adequately defining and providing examples of all three laws. Only Tarun and Floyd come close by producing adequate descriptions for third law.

Table 12. Summary of individual understanding of Newton's Laws.

Newton's Law	Good to reasonable	Fair to Incomplete	Ambiguous with examples	Ambiguous NO examples	Misconception
First law	Coby, Nazir	Tarun, Floyd,	Ray, Batuk, Gilles, Betty, Brigette	Malini, Francesca	Winona, Frank
Second law	Coby, Nazir	Ray	Malini, Francesca, Winona	Frank, Floyd, Betty, Brigette, Gilles, Tarun	Batuk
Third law	Nazir, Tarun, Coby, Floyd	Frank, Betty, Batuk	Gilles, Ray	Brigette	Winona, Malini, Francesca

Another small handful of students demonstrated fair to incomplete understandings of Newton's laws. Both Tarun's and Floyd's explanation of first law fall into this category; Ray's explanation of second law was categorize as such; and, Frank, Betty, Sabina and Batuk's explanation of third law qualify. In the case of third law, the major problems being the missing or weak explanation of paring of action-reaction forces.

The majority of students produced ambiguous definitions, some with examples and some without. For first law, the major problem was that students did not stipulate constant velocity. For second law, the problem is that students merely recited the formula, or they left out elements (most often mass), or possibly confused acceleration and constant velocity. While for third law their answers were often mere action-reaction statements.

Lastly, some showed that they had clear misconceptions of one or more of the laws. In particular, Winona demonstrated that she had misconceptions for first and third laws. Examples of third law are a real problem for several of the students because they view weight and normal as action-reaction pairs – e.g., Winona, Malini and Francesca. Batuk's explanation "It's equilibrium" betrays a profound confusion between first and second laws. He never does state F=ma or even hint at it.

4.5.2 Triangulating Interview Newton's Laws Questions to FCI Results

In order to compare the two assessments described above we scored the interview results in a similar fashion to the scoring of the epistemic models interview questions. This time our range was -1 to 4, with 4 being assigned to good to reasonable, 3 to good to fair, 2 ambiguous with examples, 1 to ambiguous without examples and -1 to misconceptions. Table 13 shows these scores.

Table 13. Triangulation of the interview Newton's Laws question to Hake FCI scores.

Program	Students	Interview Q.	Inter.Q. score averaged	HAKE
Prep.	Malini	2	0.5	.25
	Francesca	2	0.5	.24
	Batuk*	4	1.0	-.05
Honours	Betty	6	1.5	.25
	Coby	12	3.0	.82
	Winona	0	0.0	-.05
	Brigette	4	1.0	.28
	Gilles*	5	1.3	1.00
	Ray	7	1.8	.76
	Frank	3	0.8	.18
	Tarun	8	2.0	.53
	Floyd	7	1.8	.40
Regular	Nazir	12	3.0	.65

Our objective in triangulating these two assessments is not to make any grand statement, but to establish that some students' answers to the interview question were probably misleading because they performed quite differently on the FCI. Gilles in particular is a case in point. While his Hake score is 1.00 he did poorly in answer the interview questions. On the other hand, Coby and Nazir consistently showed a good understanding of the concepts of force and motion on both measures, while Malini, Francesca, and Winona consistently showed a fragile one. Note the correlation between these two assessments is relatively alpha = 0.68.

4.6 What Does Question 21 Reveal About Individual Knowledge

When we looked at other data relating to Newton's Laws, again there were surprises (see Table 14). Once again three students consistently show their understanding of third law (Nazir, Coby, and Floyd). While a couple of students appear to use better examples than they did in the interview (Betty & Brigette). This is possible due to the context. In other words, they seem to quote directly from what are probably in-class examples used by their teacher. The other five students remained somewhat consistent with either incomplete explanations (Frank & Gilles) or ambiguous answers (Malini, Francesca, and Sabina) in both the interview and in answering question 21.

Several students, however, seem to have slipped in demonstrating their understanding when it comes to the examples of third law. Tarun, Batuk and Ray, who to varying degrees (the latter two being less complete or clear) correctly related the experiences of the balloon car as an example of third law. In answering question 21, they all choose to use weaker or incorrect examples, specifically, the misconception that weight and normal are action-reaction pairs.

A possible explanation is that their mental model of third law could be described as fragile and does not distinguish between some of the nuances of the action reaction pairs of forces. Thus when asked about third law during the interview their situated knowledge about the physical models allows them to come up with good examples. Recall that these three students were strong participants in the model building and model reasoning activities. It is therefore reasonable to believe that they also had a good understanding of how third law works in the context of those physical models and not in general. This of course confirms that their understanding was fragile.

When asked again about third law in the context of the FCI questionnaire, the question is no longer situated thus they reveal the weakness in their understanding of the action-reaction pair relationship. This might have something to do with the undiscriminating resources of examples for third law, which has not yet questioned the correctness of existing examples (i.e., easily remembered naïve mis-examples). Though this is troublesome, it suggests a concrete topic that needs to be explicitly addressed in the curriculum.

Table 14. Comparison of results from two assessment instruments of Third Law

Newton's Third law	Good to reasonable	Fair to incomplete	Ambiguous with examples	Ambiguous NO examples	Misconception
Interview answers (as above)	Nazir, Coby, Floyd, Tarun	Frank, Betty, Sabina, Batuk	Gilles, Ray	Brigette	Winona, Malini, Francesca
Question 21	Nazir*, Coby*, Floyd*, Betty, Brigette	Frank*, Gilles	Malini, Francesca, Sabina	N/A	Winona*, Ray, Batuk, Tarun

* Students whose answers consistently showed the same understanding between the two assessments of Interview and FCI question 21.

4.7 Difference Between the Individual's & Group's Knowledge

Recall that at the end of the semester the physics teacher, in an attempt to get students to reflect on their experimental experience, asked his students involved in the research project to produce a group report, which addressed several concepts introduced during the research intervention (see Appendix L). We asked ourselves, what can we learn about these students' collective knowledge and ability to use models from these reports?

Thus we look at how the group answered their optional question relating to physics laws and use of models and compare this with their individual answers we reported above. We see some big differences.

Two of the three possible groups of students, Team 3 and Team 4, choose this optional assignment and produced reports. On the whole, these reports demonstrate a certain level of sophistication, which collaboration and reflective thinking typically promotes. They also show, however, that applying physics knowledge is challenging even after instruction and situated physics experiences. Each team had slightly different strengths and weaknesses in this respect, but we will focus on two aspects of their efforts to answer the questions.

We start with the Part I question: modify the Newton’s 2nd Law lab to incorporate rolling friction (Appendix L, already mentioned). This was followed up with the Part II question related to Newton’s 3rd Law: How would you further modify the lab to study the issue of propulsion?

4.7.1 Second Law Lab and Rolling Friction Question

Each team organized their answers to the rolling friction question differently. Team 3 (Floyd, Gilles and Ray) approached the problem by identifying four different types of friction, rolling friction, kinetic friction, “rubbing” friction and air resistance. Their argument consisted of the claim that, in these four instances, friction was negligible and could be ignored. Their supported their claim with explanations of the processes involved including the following: (1) generation of heat and lost of mechanical energy, (2) the rope moving faster than the pulley, (3) variation in experimental conditions due to increased mass of the cart over time, and (4) the resistance caused by air particles on the surface of the moving cart. Though some explanations were thought through, i.e., how friction might be affected by weight (mass) of the object, other explanations were not, i.e., rope slipping would affect the timing and ability to estimate velocity.

Team 4 (Frank and Tarun only at this point), on the other hand, approached the problem by concentrating on defining and describing how rolling friction worked in this case. Their argument was that though kinetic friction was not an issue, rolling friction was responsible for the movement of the cart and the turning of the wheels. Their claim was supported by detailed explanations that included notions such as: “Rolling friction is caused primarily by the interference of small indentations formed as one surface rolls over another.” They also used examples taken from everyday life to further describe how the mechanism of rolling friction could account for movement. Though they concluded with a drawing and formula for rolling friction, their representation shows a misinterpretation of the force. The students seem to have confused rolling friction, which is a backward force, with the forward force of static friction that makes things go forward (see Figure 1), e.g., the frictional force involved in walking or in pedaling a bicycle. While this is an important difference, we point out that these are sophisticated aspect of the concept of moving friction. Consequently, it is not surprising that students at this stage of physics learning (introductory course) would be having some difficulty with the direction of rolling friction.

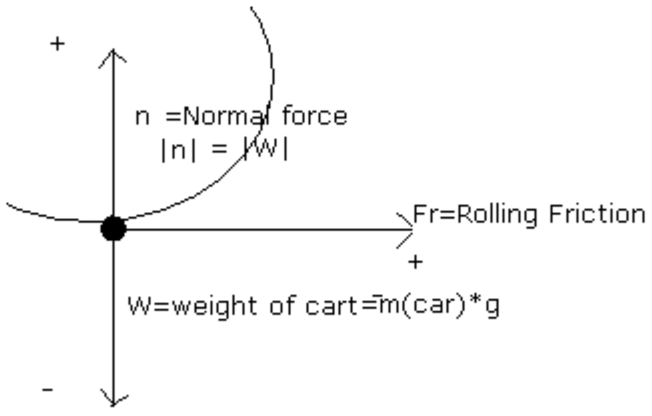

Figure 1. Drawing produced by Team 4 to describe “Rolling Friction.”

In summary, comparing the two reports we see that while both teams attempted to expand arguments that friction could be ignored (Team 3) or that friction worked a certain way (Team 4) they overlooked the data that their lab experiments had produced. Additionally, while Team 3 elaborated on the mechanisms producing the phenomena cited, they did not define the concepts. Team 4, by contrast, choose to define the concepts used and also attempted to explain the mechanisms.

4.7.2 Third Law – propulsion Question

Turing our attention to the part II question again we see that the two teams approached the problem differently. While Team 3 directly mentioned third law in their answer, Team 4 did not. That said, Team 3 demonstrated some misconceptions about this law. To start, they attempted to relate propulsion and Newton’s third law by suggesting that all propulsion is “thrust,” which they further claim is “an action-reaction pair of forces at work.” This claim laid the groundwork for their other misstatements that tie in the notion of momentum. The problem was compounded when the students attempted to explain their ideas in terms of the cart and pulley systems (i.e., the components of Newton’s 2nd Law lab), which are difficult to describe in terms of third law.

When we look at Team 4's answer, we see that though these students did not directly state third law, they made a much better explanation of propulsion. Unlike their classmates, they choose to use the example of the balloon car. Once again they clearly defined the concepts, this time adding some formality and using sources other than them themselves. Adding to this definition they provided an equation, which extends the definition making it generalizable (see below).

> *"The thrust equation shows that the amount of thrust generated depends on the mass flow through the engine and the exit velocity of the gas" (Benson). The thrust force can be derived by the equation:* $F=[(mV)_2 - (mV)_1]/(t_2 - t_1)$ *or in other words* $F_{thrust}=\Delta p/\Delta t$.

As a consequence this made it easier to follow their reasoning as they proposed ways to study propulsion and constructed appropriate tests. These ideas include running experiments, which vary the factors involved in the thrust equation (see statement below). In doing so, they also demonstrate their transfer of learning from the research intervention to this classroom activity.

> *The way that it could be accomplished would be to test the average velocity of many test runs (just like what we did) and calculate the average time and plug the values into the equation in order to find the thrust force of the air pushing out of the balloon making the car travel a specified distance.*

Another idea included changes to the mass flow rate, which result from differential densities of gases used to inflate the balloon.

> *Another interesting idea about propulsion is mass flow rate. This is calculated by mass/ time. The idea of mass flow rate would explain how the property of air in the balloon reacts over different amounts of time, making it possible to predict how far the car would go with an exact amount of air in the balloon. The mass of the air could be determined by using density. The mass flow rate could then be determined by plugging in acquired values. Another interesting test would be to fill the balloon with different gasses and find the different rates of thrust and propulsion for each different type of gas – that would be really interesting.*
>
> *Finally, in order to test the effectiveness of exhaust velocity, in our case the air coming out of the balloon, the equation* $V_e = F/m$ *should be used, where* V_e *is the effect exhaust velocity, F is the thrust force, and m is the propellant mass flow*

> *rate. This equation can be incorporated with the different gasses in the balloon and how they should react. It would be very interesting to test the different types of gasses and see which one propels the car to travel over the furthest distance in the shortest amount of time.*

Lastly, they directly relate the classroom assignment to the research experience by discussing the visualization potential of the free body diagram. They also make reference to the difference between real life and models. From these examples we might conclude that the intervention had a significant impact on these students' way of reasoning about physics, if not improving their physics knowledge.

Discussion

When we started this research project we anticipated that a model based inquiry approach to physics would provide students with a better understanding of certain physics concepts because of the affordances for learning reported in the literature (e.g., Charles, Karkin, Kramer & Kolodner, 2006; Charles & Kolodner, 2007). In addition, we anticipated that such an approach would promote students' epistemic understanding of models and their use in science. When it came to the representation transformative tools, we conjectured that they would allow students to deepen their understanding of these same physics concepts because of their affordances for mediating and helping to elicit discussion and collective sense-making (e.g., Cobb, 2002).

Lastly, we wanted to know whether the intervention promotes conceptual change specifically in regard to the physics concepts embedded in the activities. For this we used the FCI and looked at it not just with our case study sample but also with the larger population of first year science students (see Volume II for answers to research questions 4 & 5). In doing so, we addressed the following research questions in this part of the research, Volume I.

5.1 Volume I Research Questions

1. How does a model-centered intervention, designed to have certain affordances, influence students' learning of physics concepts?
   a. What cognitive, social and cultural factors influence whether these affordances are recognized and acted on?
   b. How are the intervention's scaffolding tools used – i.e., model-bridging tools? Can these tools mediate learning in this context (collaborative groups)?
2. Does this explicit reasoning with and about models influence students' understanding of models as an epistemic form?
3. What are the implications of using this intervention in a collaborative group context?

5.2 Research Question 1

How does a model-centered intervention, designed to have certain affordances, influence students' learning of physics concepts? What cognitive, social and cultural factors influence whether these affordances are recognized and acted on? How are the intervention's scaffolding tools used – i.e., model-bridging tools? Can these tools mediate learning in this context (collaborative groups)?

Learning happens through participation in activities and mediated by psychological factors such as individual cognitive capabilities, and socio-cultural factors such as sense of contribution, membership, agency, identity and so on (e.g., Holland, et al., 1998; Lave & Wenger, 1991; Wenger, 1998; Rogoff, 1990). It is a process of participating in shared enterprise and achieving joint and shared accomplishments – i.e., common ground. Knowing how to act and how to engage in joint enterprise comes through *legitimate peripheral participation* – the process by which knowledge and skills are acquired and the processes by which novices come to take on more responsibility as they identify themselves as belonging. It also comes through a sense of self (i.e., identity) as a member of the community, whatever that community might be. Identity thus mediates participation, and, in turn, is mediated by participation. More so, the possibilities of participation are shaped by the social context as well as the individual him or herself, which helps or hinders future participation – what we have described as positional identity.

5.2.1 Overview of What Was Learned About the Intervention

We do not claim statistical significance in conceptual gains, but we do claim students began to take "right actions" for learning physic as a "lived practice" and not merely as a subject to be learned by rote. What we saw in our case study was that the model-centered intervention allowed students to participate in the practices of science (i.e., experimentation) and the practices of physics (i.e., using the tools and representations of physics). In doing so, they used the tools of science and some students became somewhat proficient in the process. We also saw that working in groups, students could take on roles and identities, which, in turn, allowed them to participate in ways that could benefit the group's learning. But we also saw that students could also take on roles and identities that limit others in their efforts to participate. These are the two sides to the mediating effects of social and cultural factors on learning. In moving forward, we list what we learned in this study. In general, many of the students, in their respective groups, showed that they got better at the following practices:

1. Using tools as a bridge between different representational forms of scientific models (e.g., model-bridging tool). In doing so, they came to solve problems and build possible explanations for their ideas.
2. Designing and running experiments, which allowed them to produce their own physical phenomena. This, in turn, provided them with personal experiences to reference and recall when reasoning about the abstract models that govern the behaviour of objects in motion (i.e., Newton's Laws).
3. Becoming agents of their own learning and willing to take on responsibility for producing the requisite actions. By that we mean, they recognized a genuine need to know and understand. In doing so, they made efforts to identify or create the necessary resources, be it looking to other groups for help or ideas, or puzzling out an anomaly with more capable peers.

To help crystallize these points, we turn back to a few examples highlighted in the case reports and case studies. As well, we reference a few of the instances that appear in the corpus of data but could not be presented in this report because of the shear volume of data.

5.2.2 Using Tools

The use of the model-bridging storyboard was intended to afford certain types of discussion that might not occur otherwise. However, the manner in which the teams mutually constituted the purpose of the model-bridging storyboard tool allowed or hindered eliciting and organizing of knowledge. Both teams 3 & 4 appeared to constitute the purpose of the storyboard as a prompt to slow down the phenomena at hand (i.e., motion of the cars) and question the notion of movement as instances of transition and change (i.e., phase shifts).

How they mutually constituted the ways to use the tool was different. Team 4's discourse suggested that there was a common understanding and mutual agreement on how to approach the storyboard. Team 3's discourse suggested that at least one of the three did not. Though both teams seemed to view the tool, and perhaps the purpose of the activity, as an opportunity to use their scientific knowledge, Team 4 was better at it. Those three students, Nazir, Frank and Tarun engaged in trying out physics concepts and scientific inscriptions in an effort to integrate these pieces of knowledge into a coherent model of the physics involved in the phenomena.

Meanwhile, Team 1 was equally willing to attempt using the model-bridging tool and, in doing so, attempted to take up its affordances for reasoning about physics. They, however, lacked some of the requisite knowledge to engage in deep conversations about the forces at play and did not use the methods that the more advanced teams used. For instance, they talked about forces as 2D entities that exist on a page as lines and arrows. They did not relate the concept, or the abstract models (i.e., laws) back to the physical models. It seems, for them, these were separate events and not merely different ways of representing the same thing.

When it came to co-constructing meaning of the concepts (i.e., accumulating common ground) within the model-bridging storyboard, once again there were differences and similarities between the teams. While team 4 jointly constructed a shared understanding of static and kinetic friction, Team 3 had a more difficult time of it. We attribute the differences to subtle uses of indexical systems. Team 4 was explicit and almost textbook in the way they approached defining and identifying what they meant. Additionally, they used what was earlier described as both a verbal and gestural modes (Gilbert, 2004) to display their understanding. By contrast, Team 3 relied on the verbal mode and used unclear forms of communication to relay their ideas. For instance, the ambiguous use of "it." As researchers it was difficult to grasp what the "it" referred to was, so it wasn't surprising that the three students, themselves, were likely confused. Such ambiguities, if not clarified, make it difficult to constitute mutual understanding (i.e., a consensus model). In this case, it was clear that Ray did not have a good understanding of static and kinetic friction, and it remained unclear if the others, Floyd and Gilles, did.

5.2.3 Designing and Running Experiments

In the case report and elaborated case studies, we describe a few examples of how students came to work with models, but there was much more that we did not show. Form our data it is clear that Team 1, preparatory students, had more difficulty with running experiments and controlling error than any other single task involved in this intervention. In the early session they simply did not understand the goals of the exercise and they did not have the prior knowledge, nor they didn't know how to obtain it (i.e., didn't know that they could ask for it, in short, they needed to have agency). Later on, however, their repeated opportunities to practice, as well as their developing sense of agency, helped them in this regard.

When it came to applying physics concepts and knowledge to the actual phenomena, we saw that again Team 1 was at a disadvantage. Unlike the more capable science students, they did not use the phenomena in their attempts to understand the physics involved. Recall for example, the instance we showed where Batuk could recite second law, but had nothing to connect this knowledge to. Thus, he and the others went around in circles trying to see how it would apply to their design. As with the example of the model-bridging tool, they seemed to treat phenomena produced by the physical model and the abstract models (e.g., third law) as separate entities. Meanwhile, students in Teams 3 and 4, in particular, attended to the phenomena produced by their cars and attempted to explain them with the scientific models. Though their explanations were not with out error (i.e., some misconceptions) it was how and when they choose to apply these abstract models that was important.

Where there were some similarities between the preparatory and honours students was when it came to justification of decisions. Early on, the preparatory students seemed to defer opportunities to make decisions, but when they did, they referred to physics concepts. Though clearly notions such as friction are ubiquitous, when used in physics, there is a different meaning. It appeared that the preparatory students eventually began to use such technical physics meaning. Meanwhile, what was notable about the honours students was that they even started with the abstract model to make a design decision. Such reasoning is clearly sophisticated and reminiscent of experts in the field (Chi, Feltovitch, & Glaser, 1981).

5.2.4 Sense of Identity

A sense of group identity was demonstrated most strikingly by Team 4; and Team 2, but theirs is unproductive for learning. In this we noticed that an important mechanism was how identities interplay with social position, i.e., the ways peers help, or hinder, each other to establish status and authority to contribute to the group, what we have referred to as positional identity.

In Team 4, the three boys supported each other's ways of participating. They demonstrated that they shared a large common ground by being able to seamlessly engage in the tasks, in the process showing that they took-as-shared many of the conventions and norms of science. For example, designing controlled experiments, applying rigor and reliability, and so on. This is not to say that Team 3 and 2 did not also follow suit; but, in addition, Team 4 showed that they valued each other. Team 4 enjoyed the collaboration and helped to make each other's contributions better, in doing so, they positioned themselves as equal partners. Not so with Team 3 and Team 2, where positional identities were differentially distributed.

In Team 3, clearly Floyd, and to some extent Gilles, did not value Ray's contributions as an equal. Such is an example of how others might influence the participation of an individual member. In Team 2, the girls, predominantly, choose to position themselves as less capable when it came to many of the model-building activities. And, their unproductive group identity further influenced the individual members. This was most notable with Brigitte, who wanted to participate more fully, but was held back because, like Ray, her positional identity within the group was low. Barron (2000) writes about this in her observations of "why smart groups fail."

The truly complex story of identities is the one that emerged with Team 1. These students had identities as preparatory science students, generally not one held in high regard, but they also seemed to have identities of wanting to be more. We infer this from their participation in high school science fair projects (answers on the demographic questionnaire) as well as their decision to volunteer for this research. Though there was clear evidence that they positioned themselves as more needy (recall that they didn't take initiative in the first session) they also showed significant change over time. Their sense of self as contributing members of a functioning team took a giant step when Mike did not return. Though Malini, Francesca and Batuk did not show significant gains on the FCI, and demonstrated misconceptions in the other physics questions, we must keep in mind that they started with almost no prior knowledge of physics. What these three showed was how ones identity as a scientist, when promoted, can have substantial implications on the willingness and subsequent level of participation and may be learning somewhere down the road.

The role of roles. Before we more on, we note one more feature of positional identity and group membership. When we talk of roles we do not mean the mere taking on of a task – e.g., being the secretary. Rather, we mean the embodiment of a sense of belonging and identity that gives one the sense that they share common goals, values and beliefs with others. It also means that one wants to contribute because one's contributions will count. Students who come prepared with secure positional identities, possibly like Tarun, are more likely to try out roles and run the risk being socially ostracized. They know what to do and see themselves as fitting in. While Batuk and Malini, preparatory students in Team 1, eventually took on roles, these needed more time to develop. Nasir (2002) writes about similar phenomena with minority students.

However, Tarun, in Team 4, is a good example of a well developed role that was supported by peers. His role as "controller" of shared understanding within the group allowed his group to move forward in the construction of common ground and their consensus model of motion and forces. Unlike Ray in Team 3, Tarun was supported by his teammates in taking on this role. Unlike Ray who needed to justify his claims, Tarun used a questioning strategy to "press" for elaboration. We are told that such problematizing talk promotes deep understanding (Greeno, 2005), but here we see that it must be accompanied by positioning from the group. Tarun's role within the group promoted and sustained the type of discourse, which potentially leads to conceptual change.

5.3 Research Question 2

Does this explicit reasoning with and about models influence students' understanding of models as an epistemic form? Overall, the data from the epistemic beliefs about models questions show that our case study students, like other similar samples, started off with limited knowledge of models and how they relate to learning science. After the intervention these same students, generally, were more informed about models and were more willing to describe models as playing an important part in their understanding of science, and maybe in learning as a whole. Thus, we conclude that the intervention positively influenced these students' understanding models as an epistemic form.

5.4 Research Question 3

What are the implications of using this intervention in a collaborative group context? Is there a difference between the group's and the individual's knowledge and understanding? their group work, as a class of peers, they collectively raised important physics concerns and attempted to explain difficult physics phenomena. For example, how does the deflation of the balloon occur, and why does there seem to be a little extra thrust just before the balloon goes completely limp. These are by no means trivial to explain. Thus, we claim that it is also important to take a look at these instances of small concerns leading to big physics. In short, these issues are ones that students can relate to and sustain their interest and efforts to make sense of. No, they aren't string theory, or other such popular topics, but they are the stuff that promotes deep understanding of the basic laws of force and motion.

When these students were individually asked to explain Newton's Laws, and relate them to the physical models, the results reveal a couple of things. First, it is more difficult for these students working individually to explain the workings of a physical model using scientific models, though they seemed to engage in this talk with as a group. Second, it revealed that preparatory students were no less capable than some honours students. And lastly, it was notable that preparatory students were on average more willing to attempt this answer than some of the honours students. This in itself can be interpreted as a major influence of the intervention.

Implications for College Teaching

The results of this study have several implications for the science education. Some of these are best implemented at the program level, while others are specifically applicable to physics instruction. We describe the key implications and propose some guidelines for their use.

Recommendations for the science program

There are three main recommendations for which we provide general guides for implementation: (1) Students' epistemic belief of models is important to their learning of science. Our research shows that even short instructional treatments using models, according to guidelines, can promote a change in these beliefs. (2) Students' epistemology of science is important to their learning of science and can be achieved by providing opportunities for doing "real" science. (3) Students develop a sense of *science seeker* identities when provided with opportunities to practice science in a personally meaningful fashion that has usefulness to others. In doing so they seem to develop a sense of understanding science as more than learning equations, but also is a way of thinking (the epistemology of science). We believe this is important if for no other reason than the mere fact that they seem to take these practices of science into their every day decision making.

Guidelines for implementing these pedagogical recommendations:

1. Models need to be presented explicitly.
2. Multiple models of the same phenomena should be presented, and should be represented by at least two different media.
3. Bridging tools, such as the one used in this study, should be used to promote the link between these different media representations.
4. If computer modeling is one of these media, it should be presented after physical models to help students better understand the constructed and selective nature of models.
5. Instruction should include repeated opportunities to use and iteratively improve models.
6. Instruction should require students to share the results of their activities and be

responsible and accountable to themselves and their peers for the quality. In doing so, students are invested in their own learning and begin to feel that their contributions count.

Recommendations for the physics department

Indeed the job of the physics teacher is a difficult one. And it appears that moving students pass the Stage 1 threshold is truly challenging even when teachers use active learning techniques. We suggest that physics departments might reconsider the following:

(1) Extending the time frames available for students to learn these concepts.

(2) The use of physical tools for externalizing the learners' understanding of the inscriptions used in scientific models. Such physical artifacts promote conversation and cognitive activities, which help students to clarify meaning and coordinate their understanding through more indexical methods such as pointing to inscriptions or handling of the physical artifact. In our study, such tools allowed students to identify differences between velocity, acceleration and position. These means may be most useful for the Stage I student to promote their movement forward and pass the threshold we have identified.

(3) Specific attention to improving students' document literacy (difficulty extracting information from tables, graphs and figures) is required. We may need to explicitly teach these skills, particularly to the Regular and Preparatory students who are shown to be at Stage I in Newtonian physics. Perhaps some type of instruction that combines document literacy with other aspects of scientific practices such as experimentation might promote shifts in both document literacy with implications on physics understanding.

(4) Female students came in with less skills (Stage I) regarding Newtonian physics, however, they gain over the semester were equal to the male students, but because they start lower they end lower. Perhaps we need to focus on supporting a pre-semester introductory program – e.g., a "head-start" program for the Regular and Preparatory female students. This is supported by our case study results where the most significant changes in affect occurred with our Prep female students. Even today, girls do not get to play with cars, motors, etc. as much as their male peers.

Therefore instructional approaches such as this one may benefit girls as well as help all students with their epistemic beliefs of models.

Final Comments
Students' Point of View

In the post-intervention interview we asked students to tell us what they learned and what value the experience had for them. We were specifically interested in having their thoughts on the following questions.

6.1 Value of Making Thinking Visible

The majority of students viewed of the experience positively. These self-reporting statements of what was learned could be categorized into two types of benefits for learning: (1) those who viewed the experience of vocalizing ideas as valuable (e.g., self-explanation; see Chi, 2000); and, (2) those who viewed the experience of exchanging ideas with others as valuable (co-construction of knowledge; see among others Scardamalia & Berieter, 2003).

> *Malini: And as you know, the best way to learn something is to test it out. You know, you see it, you don't just take somebody's word for it, you know?*

> *Francesca: And, my teacher really he was, like, he was really good with uh, examples, and teaching me, so I really sort of understood it. But, this like just sort of enhanced it. So it just helped me more. Because like, the visual, things, like I could see, like, just things that I wasn't sure, like I could see that, that's how it is.*

Value of self explanation. Here are some examples of those who stated that they valued the opportunities for self-explanation.

> *Ray: The main thing I learned, like, well the first thing I really learned was, how to express myself. Because, um... Usually, when you see a problem, you know how to, you, you have your own way of going about solving the problem. It's kind of hard to articulate it in a way. Because you just like, you have an understanding. But uh, what I learned was first how, to be able to explain it to your, um, to your partners. Well once you're able to explain it to your partners I find, I was able to, once I was uh, able to do that, I got an even better*

> *understanding of what I wanted to accomplish. And ano-, and um... Working with groups was very good, because you get different approaches to the same, (gestures) problem. So, for instance, if you might have, forgotten, a certain aspect that, you just overlooked, somebody else would most likely, catch onto it. Which was a little, which I thought was uh, made it very efficient.*

> *Nazir: And also, it, the defending your own opinion and reasoning for it, it's also it's really helpful to just, you know, see the facts in a deeper way.*

> *Floyd: Yeah, that was interesting too. To you know, have someone watch you all the time... And you have to kind of vocalize everything to, because I like, I like to think internally, but you know, vocalizing, and I actually found that out, it's a good thing too. Because then you get a response from other people, so... It might be a good thing.*

<u>Value of co-construction of knowledge</u>. Here are some examples of how students viewed the opportunities to share their ideas and learn from the group discussion.

> *Gilles: I remember thinking about the balloon, balloon car when looking, the balloon was getting smaller and smaller and smaller, and the car was actually, accelerating and then slowing down, and we tried it on the simulator as well, SIMCARS, and we were like discussing ok, well how come when the balloon is half size it has the most powerful acceleration and that was interesting cause we were really thinking about different ways, how does it happen and like, oh well, it might be because of, and everyone was coming in with his own idea.*

> *Frank: I think the most important thing of this whole project was like the discussions we had. Because, you know, anyone can build a car and push it and watch it roll or get it to start moving, but the discussions we had afterward about why, and then going to the computer program saying ok, this is perfect scenario versus, you know, our floor wasn't straight, uh you know, cant have a totally frictionless surface, don't know the coefficient of friction, or whatever, and just the discussions that we as a group, like you know all teams had at the end I think was very insightful and it really helped that all groups did it at the same time so you can have your clash of ideas and then I think, you know, nine out of ten times we came to a solid conclusion and we agreed with each other and oh yeah, that's how it's done! You know, two brains are better than one, so.*

> *Frank: I liked the discussions we had, like, those were not surprising, but they were just very interesting and it was cool to see how just like a bunch of kids can really get these great conclusions from really simple models.*

6.2 Value of Cognitive Model-Bridging Tools

Usefulness of the model-bridging tool and how it allowed students to bridge their learning in the experiment back to their classroom, and vice versa.

> *Tarun: It's just, not just this, but also during the physics course, like during the year, I've noticed this change, like, it's like using more freebody diagrams, drawing more illustration, trying to figure out the problem before actually starting the problem, like the calculations and everything it seems to have helped a lot.*
>
> *Winona: Oh no, we already started doing them in class, but I don't know, before, like last year I'd never do them though, and we were doing sort of the same type of problems, I was always just kind of like oh, in this situation ok you do that I think, but yeah, and in class, I didn't really realize like the importance of them until I started like doing, building models and things and actually realizing like wow, like this makes a lot more sense to me when I can see it visually so then once I got in the habit of drawing freebody diagrams I was like ok, I think I can solve like any one of these problems.*

6.3 Value of Experimentation

First time experience for many. Though things are changing, high school students do not have many opportunities to conduct scientific experiments in high school. In our small sample over half the students claimed that their high school did not provide much in the way of science lab experiments, making this their first real opportunity to put scientific method into practice. Those who stated that these experiments were not their first either attended private or specialized high school, or attributed their unique science experience to one teacher who pushed for a different way of teaching science.

> *Malini: ...our experiments were, they weren't that accurate, but that's not the important part, the more important part is at least we got to see how it went and we looked at our certain model and said we could, we were confident that we could say this about our model, that about our model...*

Beliefs about Physics labs. When students did mention having prior experiences with scientific experimenting it was generally attributed to work done in chemistry lab. The experiments done in chemistry, however, are highly structured and more of the "cookbook" variety rather than "inquiry" experimentation. Thus, even when students had experience with scientific method, this was their first time identifying problems to investigate, designing experiments and planning how to control for experimental error.

> *Gilles: Yeah, exactly, that, it has to be like you know, explained before, ok, this is what we're going to do and here, look at the data, and this is um what we got, and this is how we explain it and instead of simply, well I have an intuition that this car might be faster than the other because I don't know, so now it was you know something serious in a certain way.*

> *Frank: You get to actually hands on, I mean we do that in the labs in class, but it was cool to kind of do it yourself, like you are the one mixing up the variables, you're, it's up to you to make sure the car runs straight, it's up to you to do all these things, to calculate, ok, which are better, and it felt more realistic than maybe a lab per se, I mean it's hard cause there's been good labs, bad labs, especially in my elemen-, uh high school, but it was uh, it was good, it was fun, but to say that it was crucial to do this, uh no.*

> *Tarun: No, and uh, yeah, about the demonstration thing, it's, it's very useful, like especially during a test like you might not exactly remember uh the law or something but if you think back to the demonstration think it's easier to remember what the results of that*

Another issue was that students did not view physics as a place for inquiry, they viewed it as known, whereas chemistry leaves room for discovery.

> *Ray: Physics, on the other hand, sure, there are many trials done, but, since you have the formulas, you kind of already know, what you should be getting. So that kind of takes away the unknown aspect of the experiment. You know what you should get, so that's what you're striving for, whereas in chemistry, it's um, there's always that doubt in your mind whether you did it properly... I think, it pushes you to do, to try and do, your very best. Whereas in physics, well there's, there's always mathematics to back it up.*

6.4 Students Final Thoughts and Suggestions

Here are some final thoughts and suggestions students made in response to the question would engage in such a project again, or recommend it to a friend.

> *Ray: I would recommend a friend, to do it. However, there's like one little aspect, I would have changed, is that, I would make it more competitive. Because I'm more competitive. I would have thought, perhaps, putting, one group, who has rubber bands, and another*

group who has balloons, and see who could go the fastest of the two. And then when you have those two components and you realize which is the best of each of the two, you can combine them. So, in that sense, but... I know a few friends who would be very interested in this. Because they like to tinker with stuff, and see how things work. And, I thought this experience was very good, because... it made me look at the aspects of physics, like outside the box. Thinking outside the box. Because when you're looking at a model, I mean, you're not part of the system. You can stand back and look at it and see it go on its own. And without actually having any implications on what's going on. So it makes you, um... understand it, without having a bias towards it.

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