INCLUSION OF THE ENERGY THREAD IN THE INTRODUCTORY PHYSICS CURRICULUM: AN EXAMPLE OF LONG-TERM CONCEPTUAL AND THEMATIC COHERENCE

by

Eric Thomas Brewe

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has been approved

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APPROVED:

______________________________, Chair

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ACCEPTED:

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Director, Executive Committee

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Dean, Graduate College

ABSTRACT

The energy thread is a logical outgrowth of the modeling theory of physics instruction; it exemplifies a conceptually and pedagogically coherent theme designed to enhance connections between models inherent in the introductory curriculum. Implementation of the energy thread requires restructuring and reorganization of the existing curriculum. The reorganization and restructuring of the curriculum is designed to reinforce expert characteristics of physicists including, coordination of representation, qualitative analysis, and flexibility of method guided by a rich knowledge base organized around a small set of general models. In-depth descriptions of the modeling tools, instructional design, and methodology are included. Comparisons based on the Force Concept Inventory, as well as on problem solutions, are made between two university physics courses, one taught with an included energy thread and another with a traditional treatment of energy concepts. The energy thread course compared favorably on all instruments. Student interviews further characterize students' use of modeling tools and problem-solving approaches as encouraged by the energy thread.

This dissertation is dedicated to those that have helped me. Special thanks go to Dr. Kissinger who encouraged scores of students to “Drive it home”. Dr. Hestenes for maintaining high standards and expectations. And most of all, my wife, who encouraged, edited, tolerated and generally supported me during the writing.

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TABLE OF CONTENTS

Page

LIST OF TABLES......x
LIST OF FIGURES......xi
CHAPTER
1 INTRODUCTION 1
Definition of Problem Solving 2
Evaluation of reform movement 4
Conceptual Reasoning 4
Role of Representation 5
Multiple methods of solving problems 6
Content Reorganization 6
Evaluation of standard curriculum 7
Energy Thread 9
Energy in other sciences 10
Benefits of energy thread 11
Energy and expert practice 13
Research Question 13
2 LITERATURE REVIEW 15
Expert/novice differences in physics 16
Expert representation 18
Expert knowledge organization 18
Representation Literature 20
Qualitative Analysis 22
Conceptual Anchors 23
Epistemological Anchors 23
Conceptual Resources 24
Epistemological resources 25
Modeling Literature 26

CHAPTER Page

Description of models ... 27

Description of modeling ... 27

Representations in modeling ... 28

Traditional approach to energy ... 29

Research into learning energy concepts ... 30

Energy representations ... 32

3 METHODOLOGY ... 35

Comparative Data ... 36

Description of the groups ... 36

Description of standard instruments ... 40

Analysis of CSEM and RAPT Data ... 42

Common Exam Problems ... 42

Common Exam Problem Assessment ... 44

Problem Scoring Rubric ... 44

Problem solving data analysis ... 47

Focus Group Interviews ... 47

Selection of interview groups ... 48

Analysis of Interview Data ... 51

4 ENERGY THREAD CURRICULUM ... 54

Modeling Background ... 54

Description of Models ... 54

Description of Modeling - Role of General Models ... 55

Description of Modeling - Role of Specified Models ... 56

Specified Model-An Example ... 57

Models as epistemological anchors ... 61

Energy as an epistemological resource ... 61

Epistemological anchors and resources in the energy thread ... 62

Model Centered Instruction and The Energy Thread Curriculum ... 63

CHAPTER Page

Role of modeling tools in the energy thread 63

Systemic tool: System Schema.. 64

Accounting Tools: Energy Pie Charts 66

Energy pie charts 67

Energy Bar Charts 69

The Equation of Everything 71

Functional Tools.. 73

Interaction Energy Graphs.. 73

Potential Graphs 75

Equipotential Surfaces... 76

Design of the energy thread 78

Three Strands of the Energy Thread 78

Modeling Strand 78

Accounting Strand.. 80

Interaction Strand 82

Energy Early, Often, Intuition... 84

Energy Early... 84

Energy Often 85

Energy Intuition.. 86

Implementation of Energy Thread Curriculum.. 87

Review of Central Energy Thread Activities 87

Central Modeling Activities – First Semester 89

Central Modeling Activities - Second Semester 100

Supporting Activities.. 106

Review of Implementation of the Energy Thread.................................. 108

5 DATA AND ANALYSIS... 111

Quantitative Data Collection... 111

Force Concept Inventory Data 112

CHAPTER Page

Conceptual Survey in Electricity and Magnetism Data 113

Rate and Potential Test Data 114

Common Exam Problem Data 115

Common Exam Problem #1 Analysis 116

Common Exam Problem #2 Analysis 119

Common Exam Problem #3 Analysis 121

Common Exam Problem #4 Analysis 123

Closer Look at Student #19 126

Problem Solving Approach Analysis 127

Focus Group Interview Data 130

Longitudinal Analysis of Interview Data 130

Summary Interview Analysis 139

Connected Knowledge Bases 140

Energy as a Ubiquitous Analytic tool 142

Models as Epistemological Anchors 143

6 DISCUSSION AND CONCLUSION.. 146

Recommendations to instructors 150

Recommendations for Further Research 152

Conclusion 153

REFERENCES…………………………………………………………………153

APPENDIX

A FOCUS GROUP INTERVIEW QUESTIONS…………………………159

B COMMON EXAM PROBLEMS………………………………………168

LIST OF TABLES

Table Page

1 Historical Description of the Comparison Groups.. 39

2 Standard Instruments used in Comparison 41

3 Problem Solving Data Collection Timetable 43

4 Schedule of Interviews... 50

5 Comparison of the General Free Particle Model and a Specified Free Particle Model.. 59

6 Central Activities to the Development of the Energy Thread During the First Semester.. 88

7 Central Energy Thread Activities, Second Semester..................................... 101

8 Supporting Activities in the Energy Thread Curriculum, First Semester........ 107

9 Supporting Activities in the Energy Thread Curriculum, Second Semester ... 108

10 Energy Thread Activities Serving Dual Purpose, Energy and Other Topic 110

11 Force Concept Inventory Pre, Post and Gain Scores 113

12 Conceptual Survey in Electricity and Magnetism Pre, Post and Gain Scores. 114

13 Problem Solving Scores from the FIPE and SCALE-UP 116

14 Represent and Analyze Scores Grouped by Correct/Incorrect 119

15 Related Data on Student #19.. 126

16 Problem #1 Data, Organized by Solution Approach 127

17 Problem #2 Data Organized by Solution Method.. 128

LIST OF FIGURES

Figure		Page
1	Example system schema	65
2	Example energy pie charts	68
3	Example of energy bar charts	70
4	Example interaction energy graph	74
5	Example potential graph.	76
6	Example equipotential surface, an electron in a constant electric field.	77
7	Problem used to introduce ‘working’	93
8	Representation of interaction energy graph from Atoms In Motion	999
9	Distribution of FIPE and SCALE-UP scores on Common Exam Problem #1	117
10	Distribution of Represent and Analyze scores on Common Exam Problem #1	118
11	Distribution of FIPE and SCALE-UP scores on Common Exam Problem #2	120
12	Distribution of Representation and Analysis Scores on Common Exam Problem #2	121
13	Distribution of scores from FIPE on Common Exam Problem #3	122
14	Distribution of scores from FIPE on Common Exam Problem #4	123
15a	Page one of Student #19’s exemplary solution	124
15b	Page two of Student #19's exemplary solution	123
16	Physical situation presented in Focus Group Interview #2	133

Chapter One

Introduction

Physics education research has to answer the question, 'What purpose do physics courses serve?' Ostensibly, one purpose of a physics course is to guide the development of novice physics students to a state of greater expertise. In accordance with this view, both the curriculum and instruction should then focus on the cultivation of expertise.

Research has revealed four traits of expert physicists: 1. Experts have a knowledge base comprised of conceptual, intuitive, and epistemological resources to draw upon, (Simon & Simon, 1978) which Reif (1984) terms amassed knowledge. 2. Experts tend to create and use many representations, both qualitative and quantitative, in solving a single problem. (Reif & Heller, 1982) 3. The representations used in solving problems, guide qualitative analysis of the situation. (Kreiger, 1987) (Mestre, Dufresne, Gerace, Hardiman, & Touger, 1993) (Chi, Feltovich, & Glaser, 1981) 4. Finally, the knowledge bases of experts are coherently organized. (Reif & Heller, 1982) (diSessa, 1983) Thus, expertise in physics involves coordination of qualitative reasoning, representation, and flexibility of method guided by a rich and organized knowledge base. In this dissertation I investigate the promotion of long-term conceptual coherence in the introductory physics curriculum to foster more expert-like practice in students.

Much physics education research is directly related to the development of expertise. A group at the University of Minnesota has studied context rich group problem solving. Many groups have done extensive research in the conceptual development of students, and still others such as the group at the University of

Massachusetts, Amherst, have looked at the role of representations in physics learning. Arizona State University's Modeling Physics Research group has investigated models as coherent units to organize the curriculum around. Other groups have focused on reinterpreting the curriculum, though these reforms primarily focus the curriculum through a lens, such as history of science, gender, or technology. While this type of reform changes the course emphasis, the course content remains the same. An analysis of the traditional content, in terms of development of expertise, will enable further evaluation of both reformed and traditional courses.

Definition of Problem Solving

Before delving into an analysis of expertise development by the traditional curriculum, it is imperative to describe what I mean by "problem solving". Simply put, problem solving is the analysis and subsequent resolution of problems. Unfortunately, this is where the definition is problematic; a definition of a "problem" is imperative. Polya, in his book *Mathematical Discovery*, (1962) states, "…to have a problem means: to search consciously for some action appropriate to attain a clearly conceived, but not immediately attainable, aim."

Much of the research into expertise is devoted to problem solving. Newell and Simon (1972) used a definition similar to Polya's in their book *Human Problem Solving*. Simon and Simon (1978) subsequently used this definition in comparing expert and novice solution strategies. Reif (1995) defines a problem solution explicitly as: "A sequence of well-specified, legitimate actions leading from the initial situation to the desired goal." Such definitions leave a broad degree of latitude in interpreting what constitutes a problem. These research groups presume that students see problems at the end of the chapter as novel situations and have to use their understanding to arrive at a solution.

Schoenfeld maintains that such "problem sets" are not problems, but instead "mathematical exercises", the purpose of which is to provide practice with some technique. He makes this distinction that Reif, Simon and Polya do not, due to the artificial nature of problem sets. Schoenfeld (1983) maintains that the models required to solve textbook problems are not robust models, and their construction does not require the same skills as construction of a robust model. Polya, Reif and Simon all acknowledge a discrepancy in difficulty between textbook problems and the type of real world problems advocated by Schoenfeld. However, Reif and Simon still view textbook tasks as demanding enough to classify them as problems.

As a member of Arizona State University's Modeling Research group, my differentiation between problems and exercises is based on the principles of *modeling instruction*. Hestenes (1987) founded modeling instruction on the principle that a small number of general models provide the structure for describing a large number of situations. Adapting these general models to specific situations involves creation of representations to aid in extraction of information contained in the model. Solving problems can be described as creating or selecting an appropriate model and extracting of specific information from it. Accordingly, Hestenes (1987) suggests classifying solving textbook style problems as directed modeling.

Traditionally, students are taught to resolve problems or exercises by creating a situation specific model exclusively using equations that allows for a solution. Students in a modeling course learn that, a robust model contains more information than is usually required to solve a specific problem; therefore solving textbook problems traditionally is more directed than creating and extracting information from a robust model. Consequently, I view textbook tasks as problems, as defined by Polya, because the resolution of these problems requires extraction of information from a model, to say nothing of the robustness of the model. For the purpose of this dissertation, I will be using these definitions of problems and problem solving.

Evaluation of reform movement

A working definition of problem solving is critical for evaluating much of the research in physics education. Having established the modeling perspective on problem solving, I can use it to evaluate some of the reform efforts in physics education in terms of how they foster expertise in novice students.

Conceptual Reasoning

Despite extensive work on reforming physics teaching, the majority of classes are still taught traditionally. Traditional classes are assessed primarily by students' ability to solve problems based on knowledge received by transmission. Success in these courses is measured by the ability to produce correct answers irrespective of the problem solving process. Students are not rewarded for their analysis of a given situation, and accordingly they focus on the answer rather than the process by which the answer is generated. As there is little guidance in the interim steps of qualitative analysis of the problem situation, students resort to memorizing algorithmic solutions. (Chi, Feltovich, & Glaser, 1981) Students end up viewing physics understanding as the ability to produce a vast set of unrelated problem solutions. This fragmented view of the curriculum is far from the coherent understanding demonstrated by experts. Many reform movements are based on engaging students in the types of conceptual reasoning that inform the analysis of problem situations. Because the emphasis on conceptual reasoning is neglected in traditional classes, these reforms have shown improvements over traditional methods. (Hake, 1996)

Role of Representation

Traditional classes primarily expect mathematical solutions to problems. Emphasis on mathematical solutions encourages students to work from the solution backwards in a 'means-ends' analysis method. (Simon & Simon, 1982) (Larkin, McDermott, Simon, & Simon, 1980b) One strategy to shift students away from means-ends analysis toward the expert practice of model generation, is to introduce, and consistently use, alternative analysis and solution processes. Experts create many representations in the analysis of a single problem; as a result, putting an emphasis on analysis requires a greater array of tools than simply equations. Graphs, Motion Maps, Vector Diagrams, System Schema, Pie Charts, Bar Charts, Equipotential Lines, and Field Lines are all examples of tools that can be used to analyze and solve problems in nonalgorithmic ways. The purpose of these tools is to have students create and use representations in the analysis of problem situations. Often, these tools are used to provide assistance in generation of a quantitative solution, though they also allow for qualitative solutions. For a further description of these tools see Chapter Four. Students in traditional classes are not introduced to alternative tools that can ease the transition from situation analysis to problem solution.

Multiple methods of solving problems

Traditional instruction tries to induce students to develop multiple strategies for solving problems by assigning copious amounts of practice problems and varying the type of problem assigned. Neglected in this methodology, is the development of conceptual resources to represent, analyze, and solve problems. As a result, students tend to memorize problem solutions without understanding how the solution is generated. Moreover, students are not provided with experience in determining which solution method is most effective or efficient. Students are left to their own devices for divining the best method to solve each problem. In contrast, developed student conceptual resources, such as a coherent set of representational tools, provides a framework for varied approaches to solving the same problem.

Content Reorganization

Many reformed classes strive to develop expertise without altering the structure and organization of course content. A sampling of the publications by the major physics education research groups in the country reveals a lack of change in the course content. ERIC searches on “physics curriculum” and “physics curriculum development,” returned a large number of articles. The majority of these articles focus on viewing the curriculum through some lens, historical, gender, technological, sociological; however, very few discussed changing physics content. Some suggested minor content changes involving modifying the treatment of energy. Omitting content development in the reform of classes leaves the content as students presently view it, a collection of unrelated topics. As Reif (1987) avers, organizing the course content in a coherent manner and making the relationships between topics explicit, is important in developing students with greater expertise.

Evaluation of standard curriculum

In order to revise the current curriculum to induce greater expertise in students, a restructuring and reorganization of the course content is necessary. The standard curriculum in Mechanics places a heavy emphasis on forces, and neglects energy. This limits the development of expertise in understanding of the energy concept in a variety of ways. In a force-centered curriculum, energy is described in terms of work, which students then view as a separate entity from energy. As a result students use forces to solve problems where energy considerations would be more pertinent.

A more balanced treatment of force and energy gives students a broader knowledge base and greater number of conceptual resources to use in the analysis of situations and problems. Moreover, by reorganizing the content, the linkages between topics can be made more explicit. The standard organization of the content neglects the relationship between force and energy by treating them as separate topics. Such isolation of topics further impedes the students' development of expertise.

The expectations placed upon students drive their learning patterns. By expecting correct solutions to large numbers of mathematically rigorous problems, traditional instruction tacitly suggests that the base units of knowledge in a physics class are the numeric solutions. To promote greater expertise, the expectations placed on students must be aligned with the characteristics of expert physicists. Alignment of these expectations with expert practice necessitates changing the structure of the course content as well as the assessments used in the course. Restructuring the course content to better reflect established expert practice includes introducing a variety of tools. Students can use these tools as conceptual resources. If success in the course requires sustained use of the tools as conceptual resources, students will comply. In-class activities, homework assignments and exams all must require use of conceptual resources to promote greater expertise. The analysis of situations and problems must be given greater importance than numeric solutions. New conceptual resources cannot be neglected; they must be repeatedly used, compared and contrasted with existing tools. To realize the changes in expectations outlined here, vast changes must be made to the structure of the traditional introductory physics course.

A conceptual and thematic thread that links the representations, the concepts and the topics in a coherent manner, as well as encourages students to use diverse approaches to solving problems has potential to reap benefits in the development of expert-like students. Balancing the treatment of forces and energy in the curriculum can have a number of benefits: providing powerful representations for reasoning and a greater array of conceptual resources, encouraging different strategies for solving problems, and making explicit topical connections that are common in the knowledge bases of experts. Furthermore, it provides means for knowledge transfer to other courses both within and outside of physics. All of these benefits are in support of expert practice in physics and can be achieved by a careful reorganization and restructuring of the course content.

Energy Thread

The ubiquitous nature of energy makes it an ideal centerpiece for reorganization and restructuring of the introductory physics curriculum. It can be woven throughout the curriculum in a way that ties together the content in a coherent manner. For this reason, throughout this dissertation I will discuss the "Energy Thread", because it is both woven throughout the curriculum and used to tie the curriculum together.

The study of energy is critical to all physical sciences. Nobel laureate Richard Feynman said that if he were to leave only one scientific idea to future generations it would be this: "…all things are made of atoms--little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another." (1963) In order to effectively study the properties of matter, energy concepts must be understood. Energy is the primary means to study the interactions to which Feynman referred.

Feynman astutely pointed to the study of atoms and interactions as the most important scientific idea. Clearly, chemistry has been based on the atomic hypothesis, but more recently, research in biology, engineering and computer science has also turned toward atomic science. The increasing importance of the atomic hypothesis has caused a greater reliance on energy concepts. Expert researchers across a breadth of disciplines depend on their understanding of energy concepts to guide their research.

Energy in other sciences

Evidence of the importance of energy concepts in physics is seen directly by surveying widely used conceptual, mathematical, and technological resources for doing physics research. Spectroscopy, used widely in Astronomy and Materials Science exploits the relationship between energy and wavelength. Spectroscopy also guided development of molecular models to include the band structure of materials, which is extremely important in Solid State Physics. Constructing explanatory models for atomic spectra was one of the motivating factors in the development of quantum mechanics. Quantum Mechanics is full of energy concepts. Hamilton-Jacobi theory is used in quantum mechanical research as well as chaos theory. The Lagrangian is intertwined with energy concepts, and is a basic tool of the majority of particle and quantum field theory research. Scattering and Resonance are widely used concepts in many areas of physics research as well. Clearly, all of these resources are dependent upon in-depth understanding of energy.

Researchers' reliance on energy concepts, in other disciplines as well as physics, is not coincidental. Generally, research depends on change, systems are studied because they have changed, or can be induced to change. In order to study change, a comparison has to be made between a system at some initial point in time, and then again at a later time. Typically this comparison is based on some observable variable, or state variable. Examples include the distance a DNA strand traveled during electrophoresis, or masses of reactants and products in a chemical reaction, or the speed at which a sub-atomic particle leaves a bubble chamber. All of these changes, in state variables, are related to changes in energy. Conservation of Energy is the overriding law that governs these changes and provides insight into the system being studied.

Benefits of energy thread

Mathematical simplicity is another compelling reason that students should receive a greater exposure to energy concepts in the introductory physics curriculum. Energy is much more facile mathematically than forces, momentum, or other vector quantities. Because energy is a scalar quantity; complexities of vector mathematics are avoided thereby averting a confusion of students.

Students should not be deprived of the benefits researchers reap in using energy concepts; and students should not be shielded from one of the most commonly used concepts in all of science. A greater emphasis on energy in the introductory curriculum encourages a development of energy concepts that are crucial if students are to continue in physics, other branches of science or even in everyday life, all of which require rich understanding of energy concepts.

Pedagogical reasons for including a greater emphasis on energy concepts are plentiful as well. System schema, energy pie charts, energy bar charts, interaction energy graphs, along with equipotential lines, and potential graphs are all useful representational tools built into the energy thread. Krieger (1987) contends that giving students the most powerful tools that are appropriate and guidance in their use would improve the quality of the class by enabling for high quality reasoning. The use of these tools guides the development of understanding of energy by giving alternate ways to represent the definition of system, Conservation of Energy, and energy transfer and storage. Equipotential lines and potential graphs are useful in representing the connection between potential energy, force and field. All of these representational tools enhance the development of conceptual reasoning skills. Adeptness at conceptual reasoning is essential for expert practice in physics. A more detailed description of these representations and their uses can be found in Chapter Four.

Providing students with a diverse tool kit that enhances qualitative analysis and conceptual reasoning is crucial to problem solving throughout the energy thread. Because students are not constrained to energy as a three-week topic that is divorced from other topics, students see energy as a useful approach to a wide array of problems. This includes problems that are often not considered energy problems, because they are typically done with forces. Inclusion of the energy thread involves solving the same problem in a number of ways on different occasions as well as analyzing the varying methods of solution. Constantly reinforcing the use of a variety of problem approaches, encourages students to use and understand a more diverse set of strategies, which is characteristic of expert-like practice.

Energy and expert practice

The facet of expertise that is developed by the energy thread, unlike other possible themes, is the development of a coherently connected knowledge base. Energy is an appropriate analytic tool for any topic in the introductory physics curriculum. Because it is appropriate across the curriculum, energy can be used to create linkages between topics. Examples of such links are: 1) Establishing the relationship between potential and field, where equipotential lines play a critical role. 2) Conservation laws are simplified by students having reasoned about conservation of energy previously. Students effortlessly pick up conservation of momentum and conservation of charge. 3) The First Law of Thermodynamics is a statement of Conservation of Energy therefore all the tools used with energy incorporate an understanding of the First Law of Thermodynamics. Using energy to explicitly emphasize the connections between topics is an important step in further developing expertise in students.

Research Question

As I have delineated here, inclusion of an energy thread in the introductory physics curriculum can have a wide array of benefits that are important both pedagogically, as well as topically. The preceding analysis leads to the research question to be addressed in this dissertation, "How does reorganizing and restructuring the course content to include an energy thread promote more expert-like practice in introductory physics students?"

This question addresses the issues I have raised in the above development. The subsequent chapters of this dissertation aim to answer the question in light of the preceding development. First, in Chapter Two, I will review the literature pertinent to expertise and the energy thread. Then, Chapter Three will provide a research methodology to address the research question. Chapter Four will explain the relationship of the energy thread to modeling instruction and will delineate how the course changes with the inclusion of an energy thread. Analysis and discussion of the data will be the bulk of Chapter Five. I will finish with conclusions and proposals for further research in Chapter Six.

Chapter Two

Literature Review

A review of the literature pertinent to this dissertation will start with a very basic review of problem solving literature, as it has been the genesis of much of the subsequent research. Among the earliest to engage in problem solving research was George Polya. His research described the use of heuristics in solving mathematical problems. Two of his important contributions were to bring attention to problem solving as a viable topic for research (1945), and in *Mathematical Discovery* (1962), he proposed a definition of a problem that was adopted and modified by others. Polya's definition of a problem is "to search consciously for some action appropriate to attain a clearly conceived, but not immediately attainable, aim." It is this definition that I will use for my dissertation, as reported in Chapter One.

Herbert A. Simon adopted a definition of "problem" that is consistent with Polya's. Based on the analysis of talk aloud problem solutions in three separate contexts: cryptarithmetic, solving formal logic problems and chess problems, Newell and Simon argue that expert problem solvers have extensive and organized knowledge bases. Analysis of experts choice of chess moves, resulted in the estimate that a chess Grand Master has a catalog of ~50,000 different scenarios. To process upwards of 50,000 chess scenarios, they argued that the problem solvers first group information into chunks, then they organize the chunks into a superstructure, which facilitates the recall of these moves. Problem solving for Newell and Simon is a search through the knowledge base, and expert problem solvers are efficient at recognizing a pattern, then finding within their knowledge base a solution. As a result, Newell and Simon assert that expert problem solvers organize their knowledge base differently than novices, and hierarchical organization of the knowledge base optimizes the problem solution search. (Newell & Simon, 1972)

Problem solving research was soon adapted to the discipline of physics; much of this research was based on the differences between experts and novices. In this section I review the expert/novice literature in physics.

Expert/novice differences in physics

Simon and Simon (1978) conducted a study examining the problem solution methods employed by two subjects on one dimensional kinematics problems. One subject was more experienced than the other. The more experienced problem solver tended to work from the problem description, using equations that have a physical interpretation and solving toward the solution; they called this a "working forward" approach. The novice problem solver tended to work "backwards". The novice generally determined what the problem was asking for and worked towards the problem definition. Typically, equations were used simply because they related the known and unknown variables, although they did not have a physical interpretation. This solution method was called a "Means Ends Analysis" method. Further, Simon and Simon claimed the expert problem solver utilized physical intuition. They described this physical intuition as an ability to mentally *represent* the problem situation in a useful manner.

They suggested the most useful representations included ways of representing interactions and constraints.

Jill Larkin and others similarly investigated the differences between the solution methods used by experts and those by novices. Larkin et al. (1980a) found that experts tended to work from the problem definition and initially made a qualitative analysis of the situation based on their conceptual and experiential knowledge base. After conducting a qualitative analysis, experts then began to develop a mathematical solution. This approach was dubbed the 'Knowledge Development' approach. Novices were found to work backwards, searching for equations that relate the known and unknown variables. Larkin described the students' 'Means Ends Analysis' approach as a search for equations without qualitative analysis.

Chi, Feltovich and Glaser (1981) tried to further distinguish problem solving techniques employed by experts and novices. Their approach was to have experts and novices categorize standard problems without having the opportunity to solve the problems. They concluded that the problem groupings made by the novice group were based on surface features of the problem, such as the similarity of objects involved. Experts were able to overlook surface features and grouped the problems according to the underlying principal needed for a solution. Differences in grouping strategies were explained by experts undertaking a qualitative analysis of the problem situation that the novices did not.

Expert representation

Chi, Glaser and Rees extended problem categorization research and drew further conclusions. Eight studies provided additional evidence of the expansive and organized knowledge bases of experts. The authors concluded that expert knowledge was organized around fundamental principals of physics, and novice's knowledge was organized around dominant objects. Additionally, they found problem representation was of critical importance to experts when solving problems.

> …the quality, completeness, and coherence of an internal representation must necessarily determine the extent and accuracy of derived inferences…Therefore, the quality of a problem representation is determined not only by the knowledge available to the solver, but by the particular way the knowledge is organized. (Chi, Glaser, Rees, 1982, p 30)

They further attributed the problem solving difficulties of novices to inadequate knowledge bases. The smaller knowledge base led to a lack of useful problem representations and solution approaches. Because their knowledge bases were underdeveloped the novices were unable to benefit from a developed intuition.

Expert knowledge organization

Fred Reif (1981) took up problem representation and knowledge organization in a number of papers. A primary difference between Reif and others investigating knowledge organization as it related to problem solving, was that Reif did not attempt to mimic expert practice but to define it; he prescribed knowledge structures that lead to optimal performance in problem solving. Reif noted that hierarchical knowledge organization facilitates the knowledge search process, which is integral to effective problem solving.

Reif and Bat-Sheva Eylon (1979) conducted a study to determine the extent to which incorporating a hierarchical knowledge organization would aid students on recall, error correction, and knowledge modification tasks. The materials used to emphasize the hierarchical organization employed a standard design. Written materials began with gross information, more minute details were omitted initially. As a greater degree of detail was introduced, statements linking the details to the preceding gross information were made; this process was carried out down to the appropriate level of detail. By linking details to gross knowledge, the knowledge base is not only organized, but made coherent as well. Throughout the materials, labels and titles were explicitly chosen and used to highlight the hierarchical organization. They found that students taught in this manner outperformed students taught in a linear fashion. Furthermore, Eylon and Reif contend that the top-down process of increasing detail used to deliver the hierarchical knowledge structure was effective and worth modeling.

The expert/novice problem solving literature provides the following insights into expert performance in physics: Experts have a greater knowledge bank than novices and their knowledge is organized differently than novices. Experts engage in qualitative analysis before attempting a problem solution. The qualitative analysis undertaken by experts relies heavily on non-mathematical representations and involves physical intuition. Experts' rich set of experiences, representational tools, conceptual resources, and problem solving approaches makes their qualitative analysis more fruitful than that of novices.

As mentioned in the expert novice literature, problem representation is an important facet of performance in experts. All representation literature is not devoted to the differences between experts and novices; accordingly, I presently review additional representation literature.

Representation Literature

Martin Krieger (1987) provides a fairly thorough description of the tools used in creating useful representations in physics. He describes the process of science as "…a craft, skillfully employing a kit of tools." Krieger describes the 'physicist's toolkit' as having three components, mathematical, diagrammatic, and rhetorical tools. Equations are the tools most employed by novices. Equations, though, make up only a fraction of the mathematical tools Krieger describes. These mathematical tools include geometry, symmetry, statistics, limits, and approximations, as well as equations. Diagrammatic tools include vectors, and graphs. Though this is an inadequate list, it broadly covers a number of the external physical representations used in physics. I believe that requiring the use of external representations in teaching novice physics students, aids them in using these tools to create internal representations of the type experts employ. Finally, Krieger describes "rhetoric tools and methods," these tools include the standard object, kinematic and causal models used in introductory physics. The rhetorical methods he describes resemble heuristics or epistemological resources employed in physics. Though not all of the tools that Krieger describes fit within the standard definition of representations, they clearly generate the representations described extensively in the expert/novice literature.

Larkin (1983) clarifies the utility of the tools described by Krieger in construction of problem representations. She distinguishes between naïve representations employed by novices and physical representations used by experts. Larkin characterizes naïve representations as ones that do not enhance solvers ability to make inferences, and cites examples such as sketches of a situation. This characterization is echoed in the work of Chi, Feltovich and Glaser. Physical representations, created and used by experts, Larkin explains this way, "…contains fictitious, imagined entities such as forces and momenta. A representation involving these entities is developed by operators corresponding to the laws of physics." The latter statement shows the agreement with the work of Krieger: tools or operators are the means by which physical representations are created. Larkin reports that students taught to create physical representations performed significantly better than those who do not. These results reaffirm earlier work done by Larkin et al., (1980a) that elaborates on the representation cycle used by experts. They found three forms of representation; labeled sketches, sketches containing physical entities, and equations. These three different representations aid experts in the following ways: qualitative evaluation of the appropriateness of the solution approach, identification of all forces and energy pertinent to the situation, and separation of the generation of equations from the analysis of the situation.

The University of Massachusetts Amherst research group has examined instructional implications of problem representation research. Use of multiple representations within the same problem was found to improve student understanding and facilitate problem solving. To encourage the use of multiple representations, they made three important instructional recommendations: They found that students needed to fully understand the representations, that teachers needed to continually utilize multiple representations in teaching and de-emphasize correct answers in grading. Though the Amherst group did not establish what is necessary to fully understand the representations, they assert this combination of measures was found to emphasize the utility and importance of representation in the analysis of problem situations. (Dufresne, Gerace, and Leonard, 1997)

Qualitative Analysis

Analysis of physical situations involves a compendium of conceptual resources. Representational tools fall into this broader category of cognitive components David Hammer has described as conceptual and epistemological resources. Hammer (2001) provided an overview of the research related to conceptual resources available to students in producing understanding. In this article he aims to extend physics education research beyond the scope of mere misconceptions to encompass student learning and knowledge production. Hammer describes a set of cognitive components including: conceptual anchors and resources and epistemological anchors and resources. He describes these cognitive components as critical to addressing any situation. The evaluation of misconceptions research and the alternate interpretation he presents is insightful, though the descriptions of the components are, in my view, inadequate. The value of Hammers’ work is predicated on a useful description of the cognitive components he identifies. I first summarize his descriptions and then elaborate upon them.

Conceptual Anchors

Hammer begins by referring to previous research, that describes raw intuitions, phenomenological primitives or anchoring conceptions, as the base which students build their understanding upon. (diSessa, 1983) (Elby, 2001) (Clement, Brown & Zeitsman, 1989) Although I agree with the conclusion that conceptual anchors are resources used in building understanding, I think Hammers' categorization of p-prims and raw intuitions as conceptual anchors is off base. The distinction between conceptual anchors and epistemological anchors is often vague. Raw intuitions and phenomenological primitives, along with some heuristics can better be described as epistemological anchors. I would describe conceptual anchors as a secondary set of grounded ideas and understandings. This description allows for varying degrees of student understanding of concepts and permits conceptions based on incorrectly applied conceptual resources and incompletely interpreted epistemological anchors. By describing conceptual anchors in this way, the previous misconceptions research is still valuable, and in addition it establishes a manner in which the misconceptions were created.

Epistemological Anchors

As I suggested, I would describe phenomenological primitives, or p-prims, and raw intuitions along with some heuristics, as epistemological anchors. Epistemological anchors are conceptions that people use to make sense of physical situations. Epistemological anchors differ from conceptual anchors, in being based on everyday experiences; they are therefore deeply rooted beliefs. (Hammer, 2001) Epistemological anchors useful in understanding physics include generalizations from experience with physical situations. An example may illuminate the concept of an epistemological anchor. Students have developed an intuitive sense that energy is related to motion. Any number of experiences may help form this epistemological anchor, including: putting gas into a car, eating a big meal after extended physical activity, or perhaps that motors have moving parts. For these students, the relationship between motion and energy serves as an epistemological anchor, as the basis for understanding anything related to energy. This suggests that instructional research should aim to identify epistemological anchors, then, design instruction around the existing epistemological anchors that promote their transformation into anchors that are consistent with scientific norms. As explained below, the energy thread curriculum identifies *general models* as ideal epistemological anchors and attempts to focus every activity around these models.

Conceptual Resources

Hammer says that the conceptual resources used in qualitative analysis of problem situations are also used for producing knowledge. The success of a student in analyzing a situation depends on the resources drawn upon in the analysis. Clement (1989) suggests bridging analogies as a critical resource for students. Elby (2001) describes the process of qualitative problem analysis as recalling conceptual resources to refine raw intuition. Either account of the process involves problem representation as a critical component of selecting conceptual resources appropriate to the situation. (Hammer, 2001)

Epistemological resources

Hammer also describes epistemological resources. These are similar in many respects to heuristics, but are perhaps more basic. I liken them to crutches used for thinking. Epistemological resources are relied upon methodologies in the analysis of situations. Hammer describes epistemological resources as being developed to manage conceptual resources. Students deploy epistemological resources throughout the analysis of a situation, managing the representations, or conceptual resources, within their model.

The epistemological resources deployed in analyzing a physical situation are not the same as used in everyday life. Hammer provides an example highlighting these differences, which I paraphrase. He cites the important practice, when solving a physics problem, of reflecting on the answer produced, on its validity and on the resources used in solving it. This he views as an epistemological resource for effective problem solving. It is unnecessary in other contexts. After solving the everyday problem of deciding what to eat for dinner. Once the decision to eat lasagna is made, it is not fruitful to review why lasagna was chosen over grilled salmon. Hammer concludes the learning of physics deeply involves epistemological resources different than those used in everyday life. In this view there exists a special subset of epistemological resources that are especially valuable for learning physics. The energy thread curriculum is designed to encourage students to use energy considerations in the analysis of physical situations and in doing so develop that subset of epistemological resources.

Research has illustrated a number of traits of expert physicists, as well as instructional strategies that lead to greater expertise among students. I have described a number of such strategies. David Hestenes has addressed a number of these strategies as elements of Modeling Research. As my research is done within the framework of Modeling Physics, it is important for me to review the modeling literature in context of the expert characteristics and instructional approaches previously reviewed.

Modeling Literature

Modeling research grew out of an in depth analysis of students' understanding of mechanics, and the instruction that allowed such understanding. The Mechanics Diagnostic Test, a precursor to the Force Concept Inventory, gave insight into what Halloun and Hestenes called 'common sense theories' of the physical world. Common sense theories emerge as students apply conceptual and epistemological resources to make sense of the world around them without appropriate epistemological anchors. The Mechanics Diagnostic provided the first quantitative data about student's common sense understanding of the world and how traditional instruction failed to replace the common sense understanding with a scientific understanding. (Halloun and Hestenes, 1985a, 1985b)

Modeling, as an instructional approach, was devised to give students conceptual and epistemological resources necessary to refine their common sense understanding into a scientific understanding of the world. Goals for modeling instruction include: a coherent understanding of the subject, delivery of both factual and procedural knowledge integral to the process of science, and a parsimonious method of achieving these goals. These goals provide the direction for model-centered instruction.

Description of models

At this point, a definition of the term "model" is imperative. Hestenes (1987) has described a model as, "…a surrogate object, a conceptual representation of a real thing." More recently, he has defined models as coherent representations of structure in physical systems and processes. (Hestenes, 1995) Models are created with representational and mathematical tools, and their ranges of applicability and validity are established empirically. These characteristics of models provide structural information that Hestenes claims is missing or unclear in traditional instruction and textbooks. One can regard models as *the* epistemological anchors for physics knowledge. Models, in this respect, serve a number of purposes. A primary function is to structure the knowledge of physics. Instead of a scattered collection of facts and formulae, knowledge of physics can be organized into a small number of models, each of which is applicable across a variety of situations.

Description of modeling

Modeling instruction engages students in the process of constructing, validating, deploying, interpreting and ramifying models. The process of modeling is a procedural component of science missing from traditional instruction, according to Hestenes. In traditional classes, the only procedural component that is explicitly taught is application of the laws of physics. The laws of physics constrain the modeling process, but, procedurally, other aspects of physics are important. The process of learning to make, adapt, use and revise models in accord with the laws of physics is central to modeling. (Hestenes, 1987)

Representations in modeling

Procedurally, the modeling process explicitly coordinates qualitative analysis and problem representation. Hestenes (1987) identifies a number of representational tools used in creating a situation specific model. One purpose of these representations is to ensure agreement between different components of the model, e.g. to check for agreement between kinematical and dynamical descriptions.

Generation and subsequent use of models are the primary activities in model-centered instruction. Accordingly, as Hestenes points out, modeling rests on a constructivist epistemology. Thus, an instructional style that is built upon a similar epistemology, such as studio-style physics, is ideal for implementing model-centered instruction. (Hestenes, 1992)

The confluence of research in problem solving, expert practice of physicists, problem representation and modeling instructional theory provides the background for my research on the energy thread. Development of the energy thread has also been influenced by research on the treatment of energy concepts in the curriculum. In this section I review that research and relate it to problem solving and modeling research. But first, I provide an overview of the traditional approach to energy.

Traditional approach to energy

Fundamentals of Physics by Halliday, Resnick and Walker, (1996) is one of the most commonly adopted textbooks for introductory physics. For an analysis of the standard treatment of energy concepts, I will examine the fifth edition of this text, as an exemplar of traditional texts.

Energy is introduced in the seventh chapter, after a full treatment of Newton's Laws. Within the first page of introduction, energy is defined as a scalar that is associated with the state of objects. Energy is described as coming in many different 'forms' or 'kinds'. This wording tends to impede the understanding of energy as a unitary concept; the different forms are simply different means to store energy. The first energy form covered in depth is Kinetic Energy, thus activating the epistemological anchor that energy is related to motion. After a short discussion of the units and equation for kinetic energy, work is introduced. Work is defined as "… energy transferred to or from an object by means of a force acting on the object." Though widely used, this definition is deficient. It overlooks the importance of *system*, and it is only valid for particles. Furthermore, Conservation of Energy has not yet been discussed, so students see no reason to believe that work can't just be produced. The rest of the chapter is devoted to different applications of the work-kinetic energy theorem.

Not until chapter eight is Conservation of Energy mentioned, and then it appears to apply only to conservative potential energies. This certainly causes problems for students in understanding that Conservation of Energy is a universal law. Once potential energy has been described, much of the rest of the development of chapter eight is devoted to explaining sign conventions for work, and developing the mathematical formalism of path integrals and dot products. Near the end of the chapter, comes the first mention of system, and the statement of Conservation of Energy. This seems pathological, energy transfers are meaningless without the ideas of system and conservation.

Traditionally, the development of energy concepts is confusing to students. Confusion results from a poor understanding of the novice student's conceptual and epistemological anchors. This confusion is propagated by failing to give students conceptual resources other than mathematical formalism for building a working understanding of energy storage and transfer. The trouble is compounded by choosing language, which distinguishes energy forms, work, heat and energy. Introducing concepts such as conservation of mechanical energy and non-conservative forces implies energy conservation is intermittently applicable.

Research into learning energy concepts

Arnold Arons was an innovator and perhaps the most influential author on reforming the physics curriculum and pedagogy. In his article, *Developing the Energy Concepts in Introductory Physics*, (1989) he outlines a number of the problems with the traditional presentation of energy concepts. He points out students' struggle with energy conservation. This is troubling for a number of reasons, especially because Conservation of Energy is one of the most prevalent and useful laws in physics, an ideal epistemological resource. This paper presents a scheme for teaching energy concepts in a more concise manner. Many of the suggestions that Arons makes are semantic in nature, but could have deep consequences. He asserts that the most glaring problem, traditionally, is that heat and work are treated as different entities residing in bodies, rather than as energy transfer mechanisms. This semantic distinction impedes students' ability to understand energy conservation by causing students to believe that heat and work are *different* than energy. Another deficiency in the treatment of energy is that the role of the system is overlooked. To be precise about energy conservation and transfer, the systems involved *must* be defined. Clear identification of the system is essential for differentiating between what Arons defines as 'real' work, (which is an energy transfer into or out of the system) and 'pseudowork', (which is a transfer within the system). Although I don't care for his terminology, the point is critical. Not only do his refined definitions of work make the Conservation of Energy more transparent, and emphasize the importance of system specification, they also agree with the First Law of Thermodynamics. Arons makes it clear that the difficulties students have with energy concepts arise from poorly defined conceptual resources for dealing with energy.

Eileen Lewis and Marcia Linn (1994) provide concrete evidence of the difficulties elaborated by Arons. They investigated intuitive conceptions held by adolescents, adults and experts. They found that many adults and adolescents believe that both cold and heat are properties of materials that flow, and that some materials hold heat or cold better than others. Lewis and Linn attribute the propagation of these models, which are inconsistent with scientific principles, to the imprecise way everyday language is used. Accordingly, heat and energy are adopted as distinct concepts unrelated to conservation of energy. Traditional presentations of energy use the language 'heat flow', which is detrimental to building scientific understanding of energy conservation, storage and transfer.

Student's understanding of energy conservation is further complicated by the prevailing belief that there are different energy forms, all of which are distinct. The research group at Universitat Karlsruhe (Falk, Herrmann, and Schmid, 1983) suggests abandoning the idea of energy forms in favor of energy carriers. This group claims that students' belief in different kinds of energy presents an obstacle, which can be overcome by the idea of different kinds of energy carriers. The energy carrier terminology has a number of other benefits, including emphasizing a substance-like view of energy, which in turn supports the idea of conservation. This group not only suggests changes in the language related to energy, but also promotes developing conceptual resources such as energy flow diagrams to enhance the understanding of energy storage and transfer.

Energy representations

The research group at Ohio State University (Van Huevelen and Andre, 2000) has done extensive work in the development of conceptual resources related to energy. Energy bar charts are a way of representing the energy in a system without worrying about exacting details of the mathematics. Van Heuvelen recommends the use of bar charts as a means to introduce energy storage and transfer qualitatively. Among the recommendations for use of bar charts, he says students must be explicit about the system but need not be concerned with the exact proportions of energy. Bar charts emphasize the idea that what Halliday, Resnick and Walker deem different 'forms' are really storage mechanisms for energy. When energy is transferred into one storage mechanism, it must have come from some other 'storage bin'. Thus, the energy in a system remains constant unless energy is transferred into or out of the system. This is a more coherent picture for students and consistent with the First Law of Thermodynamics. As a result, energy bar charts serve as a guide to the development of the mathematical representation of the First Law of Thermodynamics.

Alonso and Finn (1995), argue for anchoring the treatment of energy concepts in the First Law of Thermodynamics. The First Law of Thermodynamics is valid for all types of energy storage and transfer for a given system, not just transfers of thermal energy, as the name suggests. As it is a universal law governing every kind of energy transfer, it simplifies the subject of energy. Furthermore, it helps students reason about microscopic processes based on macroscopic measures. Alonso and Finn suggest this reasoning is facilitated by energy flow diagrams, which are non-mathematical representations of the First Law of Thermodynamics. Furthermore, energy flow diagrams equip students to understand thermodynamics, (Reif, 1999) internal energy and rest mass energy.

Clearly, the traditional treatment of energy concepts has a number of problems, generated, in part, by imprecise language in the traditional treatment of energy.

Imprecise language further corrupts the development of epistemological anchors. The only conceptual resources provided in traditional instruction about energy concepts, are equations. With only one conceptual resource, students struggle to make sense of energy concepts. The traditional treatment of energy does not recognize the existing epistemologies of students and, therefore, does an ineffective job of inducing a consistent and useful understanding of energy conservation, storage and transfer.

Chapter Three

Methodology

The energy thread exemplifies implementation of a conceptually and pedagogically coherent theme in the introductory physics curriculum, designed to cultivate greater expertise in students. The energy thread is multifaceted, both pedagogically and conceptually. Therefore, assessing the utility of the energy thread requires multiple assessments.

I expect four basic characteristics of expert physicists to develop in students exposed to the energy thread. First, students should initially address new situations by conducting a qualitative analysis. Second, qualitative analyses should be guided by explicit use of representational tools. Third, because they have been exposed to a greater variety of representations and problem solution methods, I expected students to employ a broad array of methods in solving any given problem. Finally, students should demonstrate a shift in their thinking, from seeing energy as a separate concept only useful in special cases to seeing energy as a ubiquitous tool for analyzing any physical situation. From this general view of the expectations of student outcomes, an assessment strategy can be devised. This chapter delineates, explains, and justifies the assessments used.

The energy thread provides a rich set of expected outcomes, which calls for a comprehensive assessment strategy. I aim to assess:

- Student use of representational tools to qualitatively analyze situations.
- The use of various problem solution methods.

- Student use of energy as a ubiquitous approach to analyze physical situations which unifies their knowledge base.

Assessing this set of student outcomes will allow me to address my hypothesis, that the energy thread curriculum will enhance the development of expert-like physics students. These goals are disparate, so a single assessment does not cover all outcomes. My assessment strategy involves comparisons with another physics education program, as well as student interviews to study how the energy thread guides the development of student thinking. In this chapter, I describe the collection of comparative data, the collection methods, the comparison groups, and the approach for data analysis. I describe the focus group interview process, the interviewees and the interview data analysis process.

Comparative Data

Prior to describing the comparative data, I first describe the two groups involved in the comparisons. The two groups are designated as the Energy Thread Group, and the Comparison Group.

Description of the groups

The Energy Thread Group is the Calculus-based Physics class in the Freshman Integrated Program in Engineering (FIPE) at Arizona State University. The students enrolled in the physics component of the FIPE are exclusively engineering students and are co-enrolled in Calculus, Engineering and English.

Over the last three years, the FIPE has served as an experimental classroom for the Remodeling Physics research program. The Remodeling research group has been engaged in extending Modeling Physics pedagogy to classes of larger size. During this time the FIPE course has had an average enrollment of 58 first-year students. The Remodeling Physics course has been staffed with 1 professor and 1 or 2 assistant instructors involved in the Modeling Physics reform effort. This NSF sponsored project is designed to demonstrate that the Modeling Physics methodology, which has had great success at the high-school level, can be adapted to the university classroom. Among the key components of Remodeling University Physics are: studio-style classroom, model-centered curriculum, systematic use of representational tools, modeling approach to problem solving, and integration of energy throughout the curriculum.

The comparison group is a Calculus-based Physics course for engineers at North Carolina State University. Though there are no required companion courses, the students in this class are primarily first-year engineers and are enrolled in courses similar to those of the ASU students.

North Carolina State University's physics class has been the experimental classroom for the Student Centered Active Learning Environment for University Physics, or SCALE-UP program. This widely disseminated NSF funded project has been engaged in bringing active learning teaching styles to larger university classes. A primary characteristic of the SCALE-UP program is the active learning format, in which the students are engaged in hands on/ minds on activities and are interacting with their peers as well as the instructors. The model classes of 36 students in 1998 and 1999 have been scaled up to 99 students as of fall 2000. The SCALE-UP instructors include 1 professor and 2 assistant instructors. The class does not have separate lab sections, and like the FIPE program is taught in an interactive studio-learning format. Many key components of the SCALE-UP program are similar to components of the Remodeling Physics project. Among these key components are: active learning format, physics education research guided pedagogy and classroom management techniques, and the GOAL problem solving protocol. (Biechner et. al., 1999)

Similarities between the comparison classes exist in content as well as style. Since both courses are primarily service courses for the engineering program, the content is similar as well. The syllabi and course descriptions for the two classes both list kinematics, Newtonian mechanics, energy and momentum as the focus of the first semester, and electrostatics, field, potential and magnetism as topics from the second semester. I have chosen the two samples based on the similarities between the courses, as summarized in Table 1.

Table 1

Historical Description of the Comparison Groups

	Energy Thread (ASU)	Comparison Group (NCSU)
Class Size	50+	90+
Instructional Method	Small Group Interactive Engagement	Small Group Interactive Engagement
Primary Student Population	Engineering Students	Engineering Students
2001 FCI Pretest Average	44%	48%
Course Structure	Studio Format	Studio Format
Course Materials	Real Time Physics, Chabay and Sherwood, Spiral Physics, ALPS	Real Time Physics, OCS, Workshop Physics
Problem Solving Protocol	Modeling Protocol	GOAL Protocol
Course Focus	Modeling with Energy Thread	Conceptual Development with Problem Solving

Motivation for an extensive study of the effects of the energy thread has come from a number of places. Among them is the availability of comparison of data from standard instruments across institutions. Data sharing between ASU and NCSU has yielded interesting results. During the 2000/2001 school year the SCALE-UP and Remodeling Physics courses produced nearly identical posttest scores and gains on the Force Concept Inventory (FCI) and Conceptual Survey in Electricity and Magnetism (CSEM). However, on an instrument designed to test student's understanding of potential, a concept developed by the energy thread, the Remodeling Physics students outperformed the SCALE-UP students. (Allain, 2001) This shows that the energy thread curriculum yields substantial benefits in the development of conceptual understanding, without reducing time for other crucial topics in the curriculum. Standard instruments can provide a variety of insights into the range of conceptual understanding in students.

Description of standard instruments

The Force Concept Inventory is a 30 question conceptual test which has established content validity. (Hestenes, Wells, and Swackhammer, 1992) It was developed to probe student's understanding of Newtonian concepts. Energy transcends Newtonian Theory. As a result, differences on the FCI would imply a difference in treatment of force concepts. To establish the equivalence of the treatment of forces the FCI has been administered to each class as a pre/post test.

The Conceptual Survey in Electricity and Magnetism (CSEM) (Maloney, et al, 2001) was designed as a second semester version of the FCI. The CSEM is a 32 question conceptual test, the validity has been established by the authors on an item by item basis. It is designed to probe students' understanding of topics in electricity and magnetism. Unlike the FCI, 6 of the 32 questions on the CSEM deal with energy concepts. The CSEM was also given as a pre/post test.

The Rate and Potential Test (RAPT) (Allain, 2001) is a relatively new instrument designed in two parts to assess students' understanding of rate of change and potential. The author established validity on an item by item basis, and all items were judged as valid. Because 10 of the 25 questions on this test are dedicated to concepts of potential, students exposed to the energy thread should demonstrate positive differences on this test. This test has been established as a post-test only and according to the author should be used as such.

All of the instruments used were administered as pencil and paper multiple-choice assessments. Each one was given in-class and students had 35 minutes to complete each assessment. A list of the instruments to be used to collect this portion of the comparative data can be found in the table below, along with the measured KR-20 reliability of each instrument.

Table 2

Standard Instruments used in Comparison

Instrument	Topic	KR-20 Reliability
Force Concept Inventory, (FCI)	Mechanics	0.90
Conceptual Survey in Electricity and Magnetism, (CSEM)	E&M	0.75
Rate of Change and Potential Test, (RAPT)	E&M	0.83

Initially, I designed a methodology calling for comparisons between the two groups based on the FCI, as well as the CSEM and RAPT. Unfortunately all of these comparisons are not possible. The CSEM and the RAPT were to be given during the Electricity and Magnetism course at North Carolina State University. For unnamed or unknown reasons, the CSEM and the RAPT were not administered at North Carolina State. Accordingly it is impossible to compare the two schools on these measures.

Analysis of CSEM and RAPT Data

North Carolina State did not collect CSEM or RAPT data in 2001-02, so no comparisons are possible with this class. However, both the CSEM and RAPT have been given to previous incarnations of the SCALE-UP class, so in addition to analysis of the overall scores, the class average from the FIPE program have been compared to data from previous SCALE-UP classes. This is not the initial design for comparisons, but to give meaning to the FIPE scores, baseline data is necessary. Since the individual scores are not available from previous classes, conducting an ANOVA was not possible, so the analysis of CSEM and RAPT data is less rigorous statistically, but still meaningful.

Common Exam Problems

Physics problems are and have been the most common form of assessment in traditional physics classes. Consequently, expert performance in physics is often equated with the ability to solve end of the chapter style problems. Though I do not believe problem solving is an adequate measure of expertise, much can be learned from the problem solving approach used by physics students.

During the summer prior to the onset of this study, I conferred with the instructor of the SCALE-UP class to select four problems to be given to each of the comparison classes. The four problems are given in Appendix B. Two problems were to be given during the mechanics course, and two during the electricity and magnetism course. One problem from each semester was solvable either by force or energy methods, and the other problem was solvable only by employing energy considerations. In this manner, the students' choice of problem solving approach can be evaluated.

The problem solutions were collected on midterm exams and final exams each semester, each of which last two hours. These problems were to be administered according to the schedule shown below.

Table 3

Problem Solving Data Collection Timetable

Problem Number	Acceptable Solution Method	When Administered
Mech 1	Force or Energy	Midterm, Mechanics
Mech 2	Energy	Final, Mechanics
EM 1	Energy	Midterm, Electricity and Magnetism
EM 2	Force or Energy	Final, Electricity and Magnetism

Immediately following each exam, the problem solutions were collected. The researcher first removed all identifying marks from the page, then assigned a number to each solution and finally copied each student's unscored solution. These copies have been shared by the researchers.

Like the CSEM and RAPT, the common exam problems from the Electricity and Magnetism class at North Carolina State University were not administered. As a result only the problems, Mech 1 and Mech 2 are subject to comparison between classes. All four problems from ASU were subject to the analyses and assessments I describe below.

Common Exam Problem Assessment

The common exam problem solutions have been analyzed in a number of ways, to address different student outcomes. First, these problems were analyzed to determine the level of qualitative analysis the student engaged in; second to assess by the problem solutions, is the use of a variety of problem solving methods.

In order to assess students' use of representational tools and the relationship to effective problem solving a scoring rubric was created. The rubric is based on North Carolina State's problem solving protocol. North Carolina State University's research group has established a four stage problem solving protocol to aid students in solving physics problems. The four stages are: Gather, Organize, Analyze, and Learn (GOAL) (Beichner et. al., 1999). With the GOAL protocol as a guide, I have created a scoring rubric. Because this rubric requires each of the steps in the GOAL protocol it is reasonable to expect students to satisfy all of the stages in an effective problem solution. In this way the explicit requirements on students in both participating classes are shared.

Problem Scoring Rubric

The scoring rubric has four basic stages involved in every problem solution. The stages are: Initial Analysis, Organization and Representation, Extraction of Information, and Reflection. In the Initial Analysis stage of the problem solving students generate qualitative analysis of the problem in order to devise a solution path, rather than merely grasping at equations. The types of marks that would indicate a student has made an initial analysis of the situation are: listed assumptions, definitions, models, statement of system, simplifying statements, or listing of known variables.

In the Organize and Represent stage students use the initial analysis of the situation and then generate representations, which guide the solution of the problem. A useful representation is one that allows students to extract information about the situation. Examples of such representations include: Graphs, System Schema, Vector Diagrams, Energy Pie or Bar Charts or Labeled Sketches.

The Extraction of Information stage is the use of the representations or formalism to draw conclusions about some aspect of the situation. Students who have done this will have appropriate formulae or relationships, appropriate numbers related to formulae or representations, they will have extracted intermediary information or recognized that a second iteration is necessary.

At the end of each solution, students have the opportunity to Reflect on their solution and learn from it. Tip offs that this has happened would include: comments on the numeric answer given, ideas about checking work, comments on the validity of their solution method, descriptions of other ways to do the problem, or, in the case that they do not finish the problem, comments on where they got stuck or hung up.

Each time the grader found that a student has engaged in one of the areas, a point was awarded. The score on the problem is the sum of all the points. The Initial Analysis and Reflection stages only occur once per solution, but the Organize/Represent and Extraction of Information stages can be repeated in problems that involve more than one basic step, which allows for higher scores for more complex problems. Higher scores on the problem-solving rubric should correlate with more effective problem solving strategies.

All of the students' solutions were scored by two graders individually. To establish that the graders were applying the rubric similarly, a measure of inter-rater reliability was taken. To establish inter-rater reliability a matrix of correlations between grader scores was established. Inter-rater reliability was measured on all problem solutions in the same manner. The correlation coefficients measured were r = 0.78 for problem #1, r = 0.78 for problem #2, r = 0.75 for problem #3, r = 0.80 for problem #4. This shows the scores for the two raters were correlated, so the rubric provides reliable data.

Problem solutions were analyzed in a second way as well. In order to determine the degree to which students apply varied solution methods, the problem solutions were characterized based on the solution method. For each of the four problems, all student solution approaches were characterized by the two graders independently, based on the primary physical principal used to generate a solution. The number of solution approaches was recorded for each class on each problem, to establish a characteristic for each class.

Finally, the problems were determined to be either correct or incorrect. While gross, this evaluation of the problem solutions is an important characteristic. The only problems that were judged to be correct had the exact correct answer; even when the only errors were purely mathematical the problem was judged to be incorrect.

Problem solving data analysis

The problem solving data were analyzed in a variety of ways. The problem scores from the first two problems were subjected to an ANOVA to establish differences between the two class means. Problem scores based on the rubric were subjected to a second ANOVA; in this one the factor defining the groups was whether the problem was solved correctly or not. A significant difference between the mean representation and analysis scores for the students that got the problems correct and those that did not are significant; it can be inferred that a thorough representation and analysis of a problem leads to more effective problem solutions. The final comparison between the two classes is an analysis of problem solving approaches. This data is in the form of a proportion of the class solving the problem in each way.

The problem scores from the FIPE were then subjected to additional scrutiny due to the availability of additional data. First they were correlated to FCI, CSEM and RAPT scores and course grades. These correlations may hold interesting interpretations. This amalgam of analyses should provide adequate evidence to interpret the value of problem analysis, representation and the existence of a variety of problem solving methods.

Focus Group Interviews

The most difficult, and most important, student outcome to assess is the coherence, and connectedness of the student's knowledge base. In order to assess this, I have conducted focus group interviews. Because the energy thread is not a single lesson, but a continual emphasis on energy throughout the curriculum, I do not expect students to instantaneously switch from non-energy thinkers to energy thinkers. I anticipate that students will gradually become more reliant on energy considerations over the course of time. I expect their understanding of energy concepts and the relationships between energy and other topics to develop throughout the whole course. Focus group interviews conducted at regular intervals throughout the semester allow me to characterize the development of the energy thread as viewed by students.

Because the energy thread was incorporated at Arizona State University alone, the focus group interviews were only conducted there. The basic design of the interviews is a two-group design. The groups consist of four students of mixed incoming physics experience. The first group of students was interviewed eight times at five-week intervals over the course of an entire year. This group will be referred to as the 'Yearlong Group'. In order to counter learning effects from the interview process, a second group of students was interviewed at the same intervals as the Yearlong Group. The second group will be the 'Ad-hoc Group', assembled for only a single interview. The Ad-hoc groups were composed of different students each time.

Selection of interview groups

To compose the groups I solicited volunteers on the first day of class each semester. Volunteers were asked to sign up on a sheet passed around the class. They had three levels for which they could volunteer: More than five hours, One to Five Hours, and One hour.

The Yearlong Group was compiled first. Four students were chosen from the group of students that indicated they would be willing to spend more than five hours on the sign-up sheet. From the sub-set of greatest time volunteers, I then selected four according to Force Concept Inventory pretest scores. Students were classified by high, medium and low pretest scores. The Yearlong Group had one student with a high pretest (Pretest Score > 21), two with medium pretest scores (21 > Pretest Score > 12), and one with a low pretest score (12 > Pretest Score). This classification ensured that each group was of mixed physics experience. I did not use age, gender, or ethnicity as selection criteria, as these variables are beyond the scope of this study.

After the Yearlong Group was compiled, the remaining volunteers were placed in a pool of candidates that could be called upon to be in Ad-hoc Groups throughout the year. Selection of Ad-hoc Groups followed the same routine as the Yearlong Group in so far as was possible.

Interviewees were notified approximately 3-5 days prior to the interview, and a time for the interview was established. The Yearlong Group and the Ad-hoc Group were interviewed within 2 days of each other and without a class period between them. The interviews were run according to the schedule shown in Table 4.

Table 4

Schedule of Interviews

Interview	Timing
1	Beginning of first semester
2	5 weeks
3	10 weeks
4	End of first semester
5	Beginning of second semester
6	5 weeks
7	10 weeks
8	End of second semester

In the case of educational interviews, it is important to inform students that the outcomes of the focus group have no bearing on their grade. As the moderator, I began each focus group with a reminder that the purpose of the interview is to characterize student's ideas, and the interviews did not have an impact on their grade. Vaughn, Schumm, and Sinagub (1996) provide guidelines for the moderation of such focus groups. The purpose of the moderator is to encourage discussion, but not to alter the ideas that are presented. As a result my primary function as the moderator during the questioning was to facilitate, ask for clarifications, definitions, examples and extensions when appropriate as well as note the tone of discussion.

Each focus group began with an activity, that activity served as the foundation for the discussion. Activities included physics problems, conceptual questions, demonstration of a modeling tool or simply a list of phenomena to explain. Each activity had some relationship to energy, though that relationship was not obvious. To investigate the conceptual and epistemological anchors and concepts students use to make sense of the world, they must be given the opportunity to reason without a clear guiding principal.

After an initial discussion of the situation presented, focusing questions based on establishing student's understanding of energy concepts and representations were asked. These questions make up the base set of questions, and will be repeated in slightly different forms, at each interview, throughout the process. The focusing questions used in the interviews can be found in Appendix A.

All interviews were videotaped, in order to document any work done on the whiteboard. The audio portion of the video was captured by a wireless microphone that was placed in the middle of the students. Unfortunately, during the final interview of the first semester, the batteries in the wireless microphone died at the onset of the first interview. So the only existing data from that interview are the moderators' notes. In the end, interview data was only collected seven times, rather than the eight planned.

Analysis of Interview Data

The framework for analysis of focus group data comes from Vaughn, et al. (1996) Immediately following the focus group interviews, I made notes of initial impressions of the interview and recapped what seemed to be the major themes that emerged from the interview. The next step in the analysis was transcription of each interview from the videotape. Once the interviews had been transcribed, I, along with another physicist, viewed the videotapes. During this viewing, the two viewers broke the discourse into units and coded these units. In breaking up the discourse into units, a unit represented a distinct idea that came out during the interview. The units were coded by brief descriptions of each unit. Once the units had been coded, they were categorized as to the idea in the unit. These categories were then defined as the themes for the discussion. To further generalize the discourse, I then wrote a summary of each interview based on the themes that emerged from the interview, using the discourse units as supporting evidence. These summaries were read by the other physicist and if necessary, amended. The summaries and supporting units were then used as data for analysis.

Before analysis of the development of the energy thread took place, it was important to determine if both group interviews were similar in content. If not, it is possible that the Yearlong Group was conditioned to talk about energy and in that case the Ad-hoc Group data should be treated separately from the Yearlong Group data.

It is important to keep in mind the intent of the interviews when determining how the discourse should be analyzed. Because the intent is to assess development of the energy thread, the analysis should focus on energy concept development. To do this, the interview summaries were compared as time progressed and descriptions of the differences were generated. The first round of interview data was compared to the second round data and the third to the second and so on. If students' conceptions of energy were changing, the interview summaries should be different, even though the base set of questions has essentially not changed.

The discourse was analyzed in a method that highlighted the progression of student thinking. This revealed much about the role of the energy thread in the developing physics expertise, and if the energy thread does, in fact, foster development of expert-like students.

The assessment strategy outlined here has two primary components. Included in these components is first a qualitative component aimed at characterizing the energy thread as a developmental process in students. The second part is a quantitative component designed to look at different aspects of what has been classified in the research as expert practice. When examined together, the two components of this assessment provide evidence about the development of expertise in students and the role that incorporating an energy thread plays in this process. We shall see that support for inclusion of an energy thread in the physics curriculum is strong.

Chapter Four

Energy Thread Curriculum

In this chapter I describe the energy thread in terms of the development and implementation within the context of modeling research and the theoretical and pedagogical underpinnings. I end with a review of the implementation of the energy thread curriculum in the classroom.

Modeling Background

The energy thread is a logical outgrowth of the modeling theory of instruction. In order to fully describe the energy thread, I first discuss the context of models, modeling and the relationship to the energy thread.

Description of Models

When David Hestenes first outlined modeling as an instructional theory, he was simply trying to characterize how physicists' process and organize knowledge. Expert physicists organize their knowledge around a limited number of general models. Organizing knowledge this way prevents physics from becoming an unwieldy collection of topics, too diverse to effectively manage. Physicists, however, achieve this effective knowledge organization largely by great personal effort, rather than as a result of the instruction that suggested it. Though the models, which structure and organize expert knowledge, are often not explicit; they have a general structure. Models have four essential components:

1. A system of influence, which identifies and bounds the objects involved in the interaction, as well as the interactions themselves.
2. A set of descriptors, which include object, state and interaction variables.
3. A coherent set of representations of the model, which describe the spatial relationships or the time development of the model.
4. An interpretation relating the representations, descriptors, and system of a model to a physical observable.

(Hestenes, 1987) What may seem surprising, initially, is that models are not tied to any specific scientific theory, though they are constrained to obey laws of nature. Models are internally coherent and applicable in broad varieties of situations. Theories are distinguished from models because theories are general rules that govern how models are developed and interpreted.

Description of Modeling - Role of General Models

Modeling is the process of making and adapting models to fit specific situations. To facilitate the description of modeling, I need to expand the classification of models. I recommend distinguishing between general models and specified models. *General models* have been briefly described in the previous pages and extensively elsewhere in the literature (Hestenes 1987); they are internally coherent but not situation specific. There are a limited number of general models inherent in the introductory physics curriculum, including:

1. Particle Model

2. Rigid Body Models
3. Constant Acceleration Model
4. Free Particle Model
5. Harmonic Oscillator Model
6. Field Model

This group of general models forms a sufficient foundation for the entire introductory curriculum. General models, however, are not situation specific, and accordingly information extracted from general models is also in general terms. This general information provides a template for creation of situation specific models.

Description of Modeling - Role of Specified Models

In order for situation specific information to be extracted from a model, a general model needs to be adapted to a specific situation. The creation of situation specific models, which I will call *specified models*, involves adapting and coordinating general models to fit the conditions of the specific situation. Specified models provide the solutions to standard physics problems.

Physics problems are widely used to assess students' physics knowledge. The intention is to have students create and interpret specified models. Physics problems *ideally* give students practice in identifying applicable general models, creating specified models, and then extracting and interpreting information from these specified models. A rich specified model has a wealth of information, which is readily accessible for interpretation. Standard textbook problems ask specific questions; the specified model required to answer a specific question, may include only one equation that relates the known and unknown variables. Such an underdeveloped model includes only extraction of information from one equation, neglecting important aspects of models such as measures of internal coherence, coordination of representations, or interpretation of the model. Neglecting these components of the model obfuscates the most important role of physicists, as evaluator of models.

Once a specified model has been created, students can engage in the interpretation of the model, or they can extract desired information from it. In order to extract information or interpret model consequences, students must choose an analytic approach. The physical laws guide the analysis; physics students can choose from forces, momentum, kinematics or energy approaches. The nature of the information desired from the model then guides the analytic approach employed. If acceleration of an object is the target quantity, forces often are a more efficient approach. On the other hand, if speed is the target, the optimal approach is more ambiguous. Extraction of information and interpretation of model consequences is an essential role of the physicist, and teaching this is an ideal purpose for nearly all physics classes. The ability to optimize the extraction and interpretation of models is vital in the development of expertise.

Specified Model-An Example

An example may help illuminate the role of general and specified models in a physics class. A physics class using model-centered instruction would have developed explicitly the general Free Particle Model. (Hestenes, 1987) The general Free Particle

Model is outlined in Table 5 in terms of the basic components and compared with an example specified model.

The basic components of the general free particle model are shown in the left hand column of Table 5. A list such as this, however, is useful in analyzing situations only as a template. In order to draw conclusions and interpret the outcomes from models, a general model needs to be adapted to the specific situation being analyzed. To extend the example provided in the previous paragraph, I present the following situation that requires adaptation of the free particle model: "An electron, initially at rest, is accelerated across a 5 cm long constant electric field. The electric field is created by a pair of parallel oppositely charged plates and is of magnitude 30 N/C and is directed to the left."

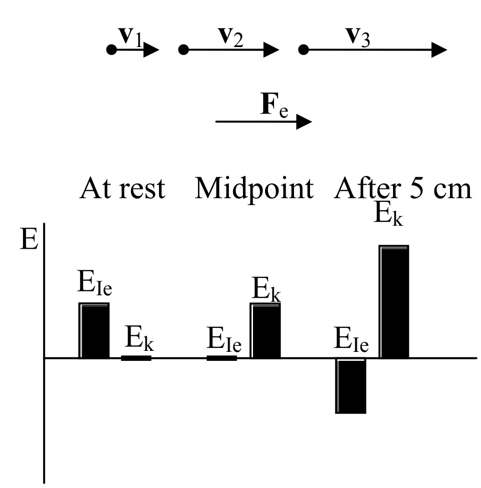
Table 5

Comparison of the General Free Particle Model and a Specified Free Particle Model

General Free Particle Model	Specified Model

• Systemic
  ○ Reference Frame
  ○ System of interacting objects
  ○ Object models
  ○ Interactions
  ○ Constraints
	• Systemic
	  ○ Electron, and charge distribution creating field
	  ○ Electron is modeled as a particle, Field is modeled as a field
	  ○ The electron and the field are interacting by an electric interaction
	  ○ $v_{electron} << c$

• Descriptors
  ○ Object
    ▪ Mass
    ▪ Charge
  ○ State
    ▪ Position
    ▪ Velocity
    ▪ Acceleration
    ▪ Kinetic Energy
    ▪ Momentum
  ○ Interaction
    ▪ Force
    ▪ Work
    ▪ Torque
	• Descriptors
	  ○ Object
	    ▪ $m_e = 9 \times 10^{-31}$ kg
	    ▪ $q_e = -1.6 \times 10^{-19}$ C
	  ○ State
	    ▪ Initial position is the left plate
	    ▪ Initial velocity = 0
	    ▪ Initial $E_k = 0$
	    ▪ Initial $\mathbf{p} = 0$
	  ○ Interaction
	    ▪ $\mathbf{F} = q\mathbf{E}$

• Representations
  ○ Kinematic Graphs
  ○ Motion Maps
  ○ Force Diagrams
  ○ Energy Bar/Pie Charts
  ○ Potential Graphs
  ○ Equipotential Surfaces
  ○ Momentum Diagrams
  ○ Force Curves
  ○ Equations
	• Selected Representations
	

General Free Particle Model	Specified Model
• Interpretations ○ Force Diagrams ⇒ Newton's Second Law⇒ acceleration ○ Energy Bar/Pie Charts ⇒ First Law of Thermo	• Interpretations ○ Force Diagrams ⇒ $\mathbf{F} = q\mathbf{E} \Rightarrow \mathbf{a} = q\mathbf{E}/m$ ○ Energy Bar/Pie Charts ⇒ $\Delta E_{Ie} = q\Delta V \Rightarrow \Delta E_k \Rightarrow \mathbf{v} = (2q\Delta V/m)^{1/2}$

The right hand column of Table 5 exemplifies the specification of the General Free Particle Model to fit the situation described above. Once the general free particle model has been adapted information can be extracted from the model or it is open to interpretation. The information that can be extracted from this specified model includes all state variables. Interpretation of the specified model includes more than simple prediction of the motion of the electron; it can be used to generate novel insight into laws of nature and relationships among those laws. Among the different conclusions students can draw about this situation, beyond the subsequent motion of the electron, are the relationships between force and energy, energy and potential, and that fields carry both energy and momentum. Imperative in interpretation of the model is the choice of analytic approach. In this example, the fact that fields carry energy would be overlooked if the specified model were only analyzed from a force perspective. Often the desired information determines the approach to extracting information from the model; however, in ambiguous situations, a number of approaches may be valid. Experts have a developed repertoire to help them choose optimal approaches. Comparing different approaches is important in developing expertise in interpretation of models.

Models as epistemological anchors

The previous example illustrates how the curriculum could be organized around a limited number of models. The free particle model would have been developed early in the first semester, and then reinterpreted in the context of electric fields. Each of the models similarly re-appears in a variety of contexts throughout the year. Through this process of reintroduction and reinterpretation, the models become epistemological anchors for the physics curriculum. Every situation to be investigated requires the identification of applicable general models and construction of a specified model. The modeling theory of physics instruction teaches students to rely on the models as the basis for understanding the physical world. For students to be cognizant of models as epistemological anchors, models must be *explicitly* identified, named, and applied.

Energy as an epistemological resource

Epistemological anchors, alone, do not constitute a sufficient understanding of physics. Instead, they provide the materials with which to build a coherent understanding of the world. Understanding the free particle model does not, by necessity, imply an understanding of all the laws governing the Free Particle Model or its interpretation in a variety of contexts. The coherence of models is short-term; one single model does not fit every situation. Families of models are internally consistent and are often represented similarly, but are, by nature, distinct. The laws of nature provide the coherent connections between families of models.

Scientists skilled at the process of modeling develop an intuition for determining which laws will be fruitful in the interpretation of the specified model. A law or set of laws that can be ubiquitously applied to make inferences from models constitutes an epistemological resource. Conservation of Energy is such a law. It is applicable across all topics in the introductory curriculum and is widely used in all of the sciences. In order to highlight this broad applicability, energy must be treated differently in the introductory curriculum.

Epistemological anchors and resources in the energy thread

I have designed the energy thread curriculum with the intention that students see models as epistemological anchors for analyzing physical situations, and that energy conservation is an ideal epistemological resource. Doing this involved, first, implementing a model-centered approach to the curriculum. Model-centered instruction engages students in creating, interpreting, and evaluating models of physical situations. Of course, this is predicated on students having a clear idea of what constitutes a model. Only after these criteria have been met, can students see models as ideal epistemological anchors for a physics class.

Having defined epistemological resources as the stable approaches used to analyze and interpret physical situations, there are a few epistemological resources that comprise the basis of introductory physics. The set of Newton's Laws make up one epistemological resource, Conservation of Energy is another. Standard curricula tend to focus primarily on Newton's Laws. The energy thread curriculum seeks to achieve a greater balance between the two epistemological resources by placing a greater emphasis on energy considerations.

Model Centered Instruction and The Energy Thread Curriculum

Models are beads on the energy thread. Because the laws of nature govern model creation and adaptation, the laws of nature connect distinct models. Furthermore, the laws of nature are applicable across any field of science, so these laws also connect separate disciplines. The energy thread approach to physics exemplifies a content reorganization and restructuring which accounts for this approach to science. Within the constructivist framework, students first need to develop the general models and understanding of their characteristics. Only then can students practice adapting and interpreting these models within the confines of the laws of nature. The energy thread plays a significant role in this cycle. Conservation of Energy, like the other laws of nature, governs the development of models. Unlike other physical laws, Conservation of Energy is perpetually useful for the extraction and interpretation of information from adapted models, making it ideally suited to introduce long-term conceptual and thematic coherence to the curriculum.

Role of modeling tools in the energy thread

The energy thread has been designed to highlight models as epistemological anchors, and energy conservation as a valuable epistemological resource. Models are dependant on the coordinated use of representational tools. The quality of the model is limited by the quality of the tools available to the modeler. Modeling tools aid in making strong coherent connections between models. There are a number of such modeling tools supporting the energy thread. Prior to describing the design and implementation of the energy thread curriculum, it is prudent to discuss the modeling tools supporting it. The modeling tools described in the subsequent section fall into three primary categories. The tools are either systemic, accounting, or functional tools.

Systemic tool: System Schema

The *system schema* serves a different purpose than other tools within the energy thread. For this reason, it is the lone member in a class of tools. System schema organize the analysis of a given situation. Inherent in the statement of Conservation of Energy, is the concept of system. Careful identification of a relevant system facilitates the use of energy concepts. The first modeling tool students encounter during the first semester that relates to the energy thread, is the system schema. The system schema is a representation of the system that includes system boundaries, all objects included in the system and all relevant interactions between these objects.

Objects in a system schema are represented without any detail. Interactions between objects are represented by two headed arrows and labeled according to the type of interaction. Finally, the system schema represents the system boundary by a dotted line around at least one of the objects. Alone, system schema do not provide predictive power to a model, but they serve the unique purpose of explicitly identifying the system to be modeled. In Figure 1, I present an example of a system schema. Earlier, in Table 5, an example situation was used to develop a specified model from a general model. I will use the same example situation throughout this section on representation. "An electron, initially at rest, is accelerated across a 5 cm long constant electric field. The electric field is created by a pair of parallel oppositely charged plates and is of magnitude 30 N/C and is directed to the left."

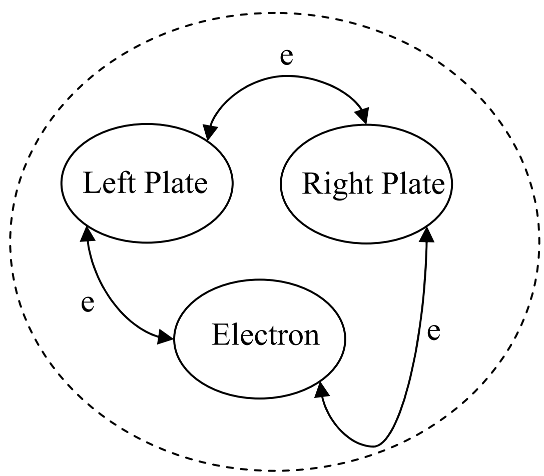


Figure 1. Example system schema

The system schema shown above clearly identifies the objects involved: the electron, and the left and right plates. The interactions between objects are labeled with an e to denote electric interactions. The system is defined as a closed system, because no interactions cross the system boundary, therefore energy will remain constant within this system.

System schemas have a number of utilities. They comprise the first level of abstraction above pictorial representation by allowing for identification of objects without concern for the structure of the objects. Additionally, the system schema aids in the creation of basic energy arguments based on conservation. Local energy conservation or non-conservation is dependant on a defined system; the schema provides an outlet to make the system definition explicit. As shown above it is easy to determine the energy in the system must remain constant, because nothing crosses the system boundary.

Focusing the students on the interactions between objects assists in the creation of the field model. The concept of energy storage in a field is efficiently developed if students agree that interaction energy cannot be stored in a single particle, but requires an interaction. Then the field can be modeled to mediate the interaction between two objects and can store and transfer energy and momentum. The example system schema highlights this subtle detail by making the interaction explicit which contributes significantly to the construction of the field model by representing the interaction between charged particles as an electric interaction. Without system schema, the field model can appear unjustified and counterintuitive.

Students use system schema in the qualitative analysis of situations. Routinely, students report that the system schema is the most useful tool throughout the course. I believe this is because it provides students a basic first step in solving problems or analyzing situations. It helps organize the relationships between objects. Without this organization, students find themselves overwhelmed with the difficulty of starting a solution.

Accounting Tools: Energy Pie Charts

The second category of modeling tools in the energy thread are the accounting tools. Energy pie charts, energy bar charts, and the First Law of Thermodynamics all represent the storage and transfer of energy. Accounting tools are used to keep track of energy within a system, including transfers into or out of the system. There is a strong analogy between energy storage and transfer and money storage and transfer in banking. Traditional treatments of energy are primarily exercises in accounting, and the only tool used is the First Law of Thermodynamics. Accounting tools not only describe energy storage and transfer, but also emphasize the unitary nature of energy and promote understanding of the concept of conservation.

Energy pie charts

Energy pie charts are visual and conceptual representations of energy storage and transfer that emphasize the universal nature of energy. Each pie represents the energy in the system. Energy transfers into the system are accompanied by an increase in size of the pie, and conversely, transfers out of the system decrease the size of the pie. Pies are divided according to the energy storage mechanisms being used. Practically, the divisions are not necessarily representative of relative amounts of energy, this shifts the focus away from equations toward a thorough qualitative analysis. By changing the division of pies as time progresses, energy transfers within the system are represented. In Figure 2, I create a set of energy pie charts based on the system schema from the previous section.

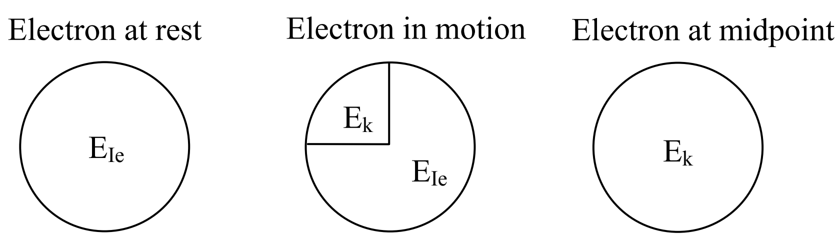


Figure 2. Example energy pie charts

In the pie charts represented above, the pies are all the same size, representing energy conservation within the system. As the electron moves from the negatively charged plate toward the positively charged plate, the kinetic energy increases, showing that the electron is accelerating. The electric interaction energy, E_{Ie}, decreases to zero directly in between the plates. While this example shows the utility of the energy pie charts in the representation of energy storage and transfer, it also demonstrates a limitation of the pie charts. Beyond the halfway point the electric interaction energy continues to decrease and the kinetic energy continues to increase. However, the electric interaction energy becomes negative, which is not represented well on energy pie charts. This failure provides motivation for energy bar charts, which I will discuss momentarily.

Pie charts exist within an intermediate level of abstraction; students can focus on energy storage and transfer in the system, but not concern themselves with the mathematics. Using energy pie charts in conjunction with system schema, students are able to make more sophisticated energy arguments because energy pie charts provide a visual representation of energy conservation. Energy pie charts are also used to preempt certain misconceptions. Energy pie charts are introduced before energy bar charts in order to combat the belief that there are a number of disparate forms of energy. With pie charts, the energy is a unitary quantity that is merely stored in different mechanisms rather than in different forms. The second misconception energy pie charts combat is the notion that energy is 'lost.' Students are forced to account for all of the energy in the system; therefore, it is acceptable to describe energy leaving the system, but not to say that it is lost. This requires students to establish energy storage mechanisms for the energy that was previously 'lost'.

Energy Bar Charts

Energy bar charts are very similar in nature to energy pie charts, but have the ability to represent negative energy. Similarities between pie charts and bar charts include the total height of the bars represents the energy in the system, and the different bars represent different energy storage mechanisms. In addition to the ability to represent negative energy, the bar charts are different in that they are more suited to quasi-numeric calculations. Using the electron in a constant field as an example, the following bar charts demonstrate the similarities and differences between bar charts and pie charts.

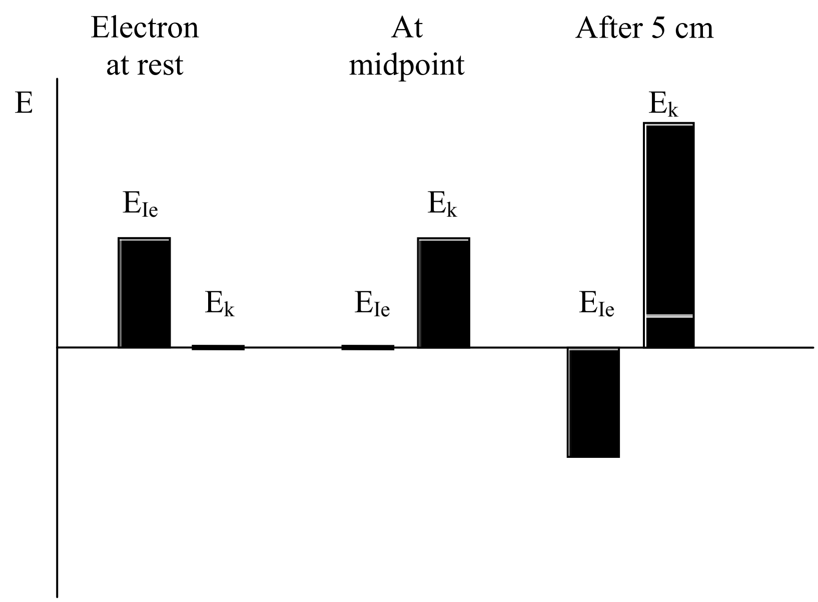


Figure 3 Example of energy bar charts

Energy bar charts are introduced later than energy pie charts for a number of reasons. First, because energy bar charts separate energy storage into different bars; bar charts support the idea that energy exists in a number of disparate forms. Introducing pie charts first emphasizes the unitary nature of energy. Bar charts also lend themselves to more quantitative analysis; in the energy thread curriculum, I prefer that students focus on qualitative analysis of situations before doing any calculations.

Energy bar charts are introduced out of necessity. To develop an instinctive sense about energy conservation, energy pie charts, which represent energy as a holistic positive quantity, are introduced first. After some practice with energy pie charts, students feel comfortable with the concepts of conservation and the unitary nature of energy. Introducing negative energy is not necessary until universal gravitation is introduced. The introduction of energy bar charts preserves Conservation of Energy by allowing negative energies to be represented. Energy bar charts are ideal for representing negative energy because energy bar charts are more quantitative than pie charts. In the example energy bar charts, beyond the midway point of the electron's path the electric interaction energy becomes negative. The total energy is calculated by adding the height of the kinetic energy bar, to the height of the electric interaction energy bar, which is in the negative direction. In the end the result is the total energy is constant in concurrence with Conservation of Energy.

The Equation of Everything

The *"Equation for Everything"*, or as it is more commonly known, The First Law of Thermodynamics defines local energy conservation. It is the equation that accounts for energy storage and transfer within a system. All other representations of energy in a system are governed by the Equation of Everything. This equation is the reason energy considerations have predictive power.

The Equation of Everything, however, is the most abstract representation of a physical system. For this reason, it is beneficial to represent the energy in the system first with a visual and conceptual representation, such as with energy pie or bar charts. Ideally, the Equation of Everything can then be written as a direct interpretation of energy pie or bar charts. While it is true that the Equation of Everything can be written simply from an analysis of the situation, doing this requires implicitly considering multiple levels of abstraction. Introducing other representations of the energy in the system first lessens the "Shock of Abstraction" by first explicitly considering less abstract representations. I liken it to jumping from a sauna to a bucket of ice, compared with a cold shower to a bucket of ice. The visual representations ease the transition. Accordingly, the Equation of Everything is not introduced as soon as energy is considered, but after students have been allowed to use and interpret the less abstract representations.

The Equation for Everything for a specific situation can be constructed through direct interpretation of the energy bar charts and system schema. The First Law of Thermodynamics, states: $\Delta E = E_W + E_Q + E_R$, or the change in energy of a system equals the sum of the energy transferred into or out of the system by working, heating and radiating. In the example system schema, since no interaction crosses the system boundary, there can be no energy transferred into or out of the system, so $E_W + E_Q + E_R = 0$. Energy can only be transferred within the system. The sum of the energy transfers within the system must also be zero. Then working from the energy bar charts, since the only energy transfers are the change in E_k and the change in E_{Ie}, these changes must be of the same magnitude, $\Delta E_k + \Delta E_{Ie} = 0$.

The First Law of Thermodynamics ultimately is the basis for energy accounting, but the coordinated use of energy accounting tools provides a coherent method for students to develop the abstract quantitative representation.

Functional Tools

A third category of modeling tools exists within the energy thread. These tools relate energy to other topics within the curriculum as well as allow for development of functional relationships between topics within the energy thread. These tools include interaction energy graphs, potential graphs, and equipotential surfaces. Energy accounting tools represent the energy in a system. Occasionally, it is of interest to focus on the interactions and only represent the interaction energy. The functional tools represent or can be interpreted to represent the interaction energy in the system.

Interaction Energy Graphs

Interaction energy graphs represent only the energy between two particles. Interaction energy graphs are among the most widely used representational tools; both physicists and chemists use them to explain a variety of phenomena. Among the phenomena that can be explained based on interaction energy graphs are: binding, cohesion, compressibility, conductivity, frictional energy transfers, phase changes, physical bonding and thermal expansion. Figure 4 represents the interaction energy graph for the electron in the constant field example.

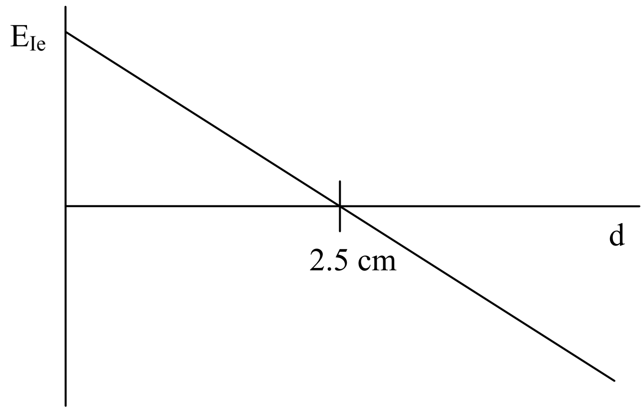


Figure 4. Example interaction energy graph

In the example with the electron between two parallel plates, the two plates are treated as one object, and the interaction energy is the result of the interaction between both plates and the electron. The interaction energy graph shows a linear function for interaction energy, the slope of which is a constant. This means the force on the electron is a constant anywhere between the two plates, and therefore the field is also constant between the plates. Noticing that the slope is negative, means the force on the electron must be positive, or to the right, which can lead to an inference about the orientation of the two plates.

The relationship between force and energy is represented effectively with interaction energy graphs, the force between two particles can be found by the negative slope of the interaction energy graph. By exploiting this relationship, equations describing the energy stored in a spring, internal energy due to friction, and gravitational and electric interaction energies can all be developed analytically. Relating force to energy is an important component of the energy thread. It is through these types of relationships, the energy thread ties together the curriculum.

Interaction energy graphs also allow for evaluation of models. Students are initially taught E_{Ig} = mgh, however, this model is only valid near earth's surface. When the mgh model is extended to a height of infinity, the model breaks down. This model breakdown provides the motivation for universal gravitation. Interaction energy graphs represent the ranges of validity for the two models. Near earth the graph of gravitational interaction energy appears linear, and has a slope of –mg. However, that only holds true when the energy can be linearized. This interpretation is difficult without the use of interaction energy graphs.

Potential Graphs

A modeling tool used in essentially the same manner as interaction energy graphs are *potential graphs*. The primary difference is just a matter of scaling, interaction energy graphs represent the energy between two particles and potential graphs represent the possibility for an interaction energy. Potential graphs allow you to represent only one particle. Instead of interpreting the interaction energy graph to find the force between particles, potential graphs can be interpreted to find the field of the particle by taking the negative derivative. Potential graphs close the loop by relating field to force to interaction energy back to potential; as a result, they play an important role in the energy thread curriculum.

In Figure 5, I use the example situation of an electron in a constant field and have created an example potential graph. Again the differences between potential graphs and interaction energy graphs are differences of scaling. The potential shown is the potential for the two parallel plates. The slope is constant, so the field must be constant, and because the slope is positive, the field must be in the negative direction, or to the left.

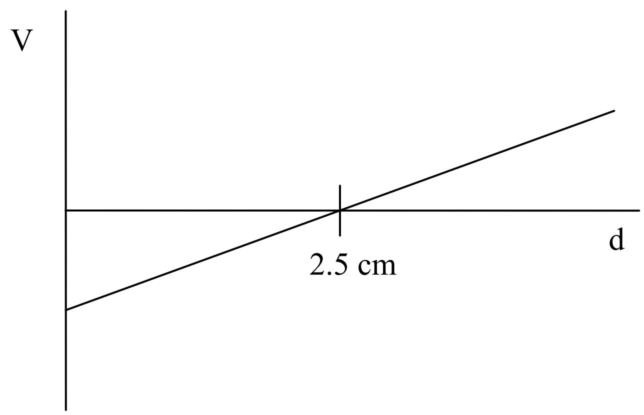


Figure 5. Example potential graph.

Equipotential Surfaces

Equipotential surfaces are the final modeling tool I will describe. Equipotentials are two-dimensional spatial representations of potential. In many respects they are identical to potential graphs, but they are not confined to one dimension. Equipotentials as the name implies, are lines along which the potential is equal. Equipotentials can be used to reason about forces, and fields. Again, because they relate forces to energy, they are useful within the energy thread curriculum. In practice, equipotential surfaces are used frequently, in weather maps and geographic relief maps, which can connect their physics knowledge to real world applications.

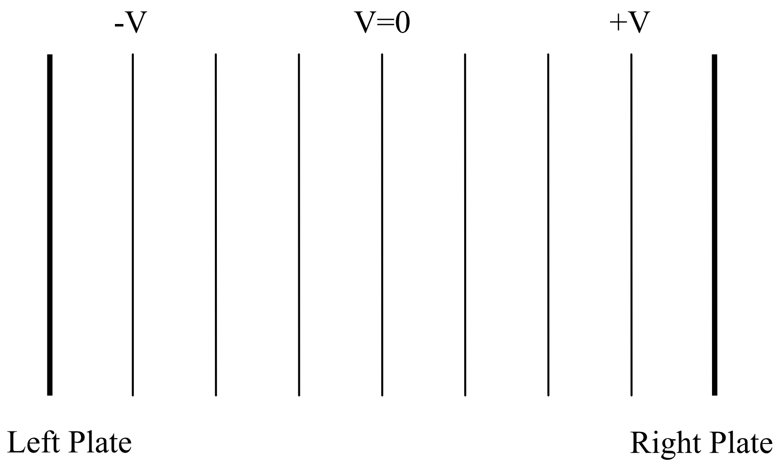


Figure 6. Example equipotential surface, an electron in a constant electric field.

Figure 6 shows the equipotential surface for the example situation, an electron in a constant field. Again because the equipotential lines are equally spaced, the field must be constant. With potential graphs, the negative slope of the line defined the field, equipotentials are two dimensional, therefore the multidimensional slope or the gradient is used to calculate the field. The gradient in this case points to the right, so the field points to the left.

There are a number of other modeling tools including, kinematic graphs, motion maps, force diagrams, momentum vectors, field lines and field vectors; all of which are used in the energy thread curriculum, and all of which are, at some point, related to energy. What I have presented are the essential modeling tools for the energy thread curriculum. The description of these tools should be sufficient to understand the use of modeling tools in the subsequent discussion of the design and implementation of the energy thread curriculum.

Design of the energy thread

In the following sections, I describe the theoretical underpinnings that guided the design of the energy thread curriculum.

Three Strands of the Energy Thread

Energy conservation is a law simply stated, which has many subtle nuances. I attempt to explicitly address many of these subtleties in designing the energy thread curriculum. To this end, I identify three strands that when braided together make up the energy thread. The three strands are the *accounting strand*, the *interaction strand*, and the *modeling strand*. In this section, I describe each strand and its role within the energy thread curriculum.

Modeling Strand

The modeling strand is almost never identified as an important component of the treatment of energy. However, this strand comprises some of the most critical and definitive choices in using energy to interpret specified models. Preliminary decisions to be made in the construction of specified models make up the modeling strand.

Among the preliminary decisions to be made within the construction of a specified model is the definition of system. This definition is of critical importance. Without a clearly identified system, there are no bounds on the transfer of energy, and therefore energy conservation is meaningless. The modeling strand makes students aware of the need to explicitly identify the system. One of the advantages of using system schema as a modeling tool is that it helps students to explicitly identify the objects within the system and the system boundaries. With this explicit distinction alone, students can make powerful qualitative arguments about the energy in the system.

Other elements of the modeling strand also need to be addressed explicitly, including the geometric models of the objects in the system. In order to adequately describe the storage and transfer of energy, the object models must be specified. The choice of object models is needed to ensure the specified model is self-consistent. For an object to store energy internally, there must be a means by which to store the energy. For example, a structureless particle does not have any internal means to store energy, therefore all collisions involving structureless particles are perfectly elastic collisions. Though this may seem like a trivial detail, it has broader implications later, when models of solids and liquids are constructed. Ideally, students are confronted with decisions concerning the appropriate object models early in the curriculum, this way they recognize the model chosen is an important decision. The energy thread, as I have implemented it, has the students first encounter this decision in the third week. In turn, they are able to critically evaluate the validity of their models throughout the year.

The third component of the modeling strand is that students must make decisions about the level of detail required of their model. Models are never complete, greater levels of detail can always be achieved through more sophisticated modeling practices. However, model parsimony is often a desired trait of specified models; if a simplistic model will allow for adequate information extraction or inference, then simple models are preferable.

The preliminary phase of the modeling process generally ensures creation of a model that includes adequate detail. When students make the decisions that are typical of the modeling strand such as, defining the system, choosing the object model, or appropriate representational tool, they have taken the first step in this process. The modeling strand helps students recognize the importance of these decisions and the impact they can have on the model. For example, a model of a gas that does not include interactions between particles does not include adequate detail to explain phase changes.

These three components of the modeling strand are often ignored or treated implicitly in the standard treatment of energy. The energy thread curriculum makes these three components explicit early in the year. Students' ability to critically evaluate models and their outcomes relies heavily on the system definition, how the objects are modeled, and the level of detail included in the model.

Accounting Strand

The accounting strand is the most basic and most essential strand. Textbooks tend to cover accounting of energy and neglect other considerations. The accounting strand is where the numerical tabulation of energy takes place. In this section, I will describe the accounting strand of the energy thread.

Conservation of Energy is the law that defines the accounting strand. Because it is a law which provides predictive power, it tends to be the focus of the energy treatment of most physics classes. Unfortunately, most treatments of energy are inadequate. Simply having students calculate energy before and after some event, and then blindly setting the energies equal does not represent a *comprehensive* treatment of energy concepts.

Conservation of Energy, or the First Law of Thermodynamics, is a statement of energy storage and transfer. Implicit in this statement is the concept of system as described in the modeling thread. Also contained in this statement is the unitary concept of energy. Energy is a state variable of systems, which can be stored and transferred. When energy is stored or transferred, a new substance is not created, but the same energy is redistributed. The current treatment of energy abuses the unitary nature of energy. On one hand, students routinely calculate energies and exploit the unitary nature of energy; but when considering the quantity of work, they do not recognize it as an energy transfer by mechanical means. Instead, work is treated as if it is a different quantity altogether.

In order for students to effectively use conservation of energy, they must recognize that energy stored or transferred is equivalent. In order to address this in the energy thread, the vocabulary of energy has to be modified. Instead of 'work', which implies a quantity different than energy, we talk about 'working' as an energy transfer process by mechanical means. Energy pie charts and bar charts further cement this understanding, by representing the energy in the system holistically. Energy changes in the system necessitate an energy transfer into or out of the system, which only occurs with working, heating or radiating. In this way, the energy thread is consistent with The

First Law of Thermodynamics, which Alonso and Finn call "The Equation of Everything". (Alonso and Finn, 1995)

The accounting strand is the only strand explicitly treated in the standard curriculum. There is good reason for this; I believe it is due to the mathematical simplicity of energy considerations. Because energy is a scalar quantity, students are only required to use algebra, whereas with forces, momentum, or kinematics, geometry is often required. Though students in calculus based physics classes can handle geometry, it is cumbersome and often unnecessary. As the energy thread is woven backwards into earlier and earlier science courses, the mathematical parsimony grows in importance. One way the energy thread differs from the traditional energy treatment is that energy is treated in parallel with the other topics, forces, momentum and kinematics. In this way, students are encouraged to develop at least two strategies for approaching problems. Traditionally, energy is treated *after* forces; students then develop one approach to problems that they are comfortable with. Energy becomes a secondary approach and the mathematical simplicity of energy is lost to the students.

Interaction Strand

The third strand of the energy thread is the interaction strand. The interaction strand is perhaps the most fundamental strand. Physics is essentially about describing and predicting the outcomes of interactions. Energy is ideally suited to this purpose for a variety of reasons. Primarily, energy deals with the time development of systems. Because systems change as result of interactions, energy is appropriate to describe change. At the introductory level, almost every change in a system is accompanied by an energy transfer. This is the reason energy is a fundamental state variable, and is the primary justification for an energy thread curriculum. Because changes within a system require a transfer of energy, energy is always a useful tool for investigating change.

Changes within systems result from interactions. Interactions can be described in various ways. Forces, and energy are the primary methods of describing interactions. At the introductory level, every interaction could be described either by a force or by energy. Since either a force or energy can both be used to describe the same interaction, there must be some relationship between forces and energy. The quantities that relate energies to forces are the field and the potential. By focusing on these quantities, and how they relate force to energy, the laws governing the creation, adaptation and interpretation of models are related. Emphasizing the relationship between force and energy is a primary focus of the energy thread. This tends to lend even greater coherence to the curriculum. Furthermore, without an overt focus on energy storage and transfer, a justification for the field or the potential is lost.

Storing energy in interactions rather than in objects provides the justification for the difficult concepts of field and potential. When energy is stored in objects, the concept of field provides no novel predictive power. However, when energy is stored in interactions, then field becomes the mitigating factor in the interaction, so energy and momentum can be stored within the field. If energy is stored in the interaction, the field then has an explicit purpose, which is emergent from the analysis of situations.

Concepts of field and potential are very important in the energy thread. They relate forces and energy. An outcome of this relationship is the conceptual cohesiveness of the curriculum. With this outcome in mind, the energy thread has to make subtle, but very important changes to the structure and organization of the curriculum. The difference between storing energy in interactions, rather than objects, may seem slight. After repeatedly hearing about the potential energy of an object, it is no surprise students are confused by the statement that energy is stored in fields. By preempting this misconception with a careful choice of language, the energy thread gains efficiency in the treatment of fields.

Energy Early, Often, Intuition

In order to effectively address the three strands of the energy thread and convey energy as an epistemological resource, I adhere to a simple design principal; introduce energy early, often and always in terms of developing students' energy intuition. Following I describe this design principal, and how it influences the energy thread.

Energy Early

A common flaw in the standard treatment of energy is that it allows students to employ only one single analytic approach to solving problems. Because the standard curriculum is force-centered, students attempt to use forces to solve problems even when it is not appropriate. Many of the students in a university physics class have taken high school physics. As a result, they have a strong affinity to using forces. In order to overcome this force affinity, it is important to introduce energy as an analytic method early in the semester. By introducing it prior to forces, energy gains standing as a useful analytic approach.

Energy can be introduced as soon as dynamic situations are considered. In this manner, students first see energy as a useful tool for analyzing dynamic situations. These methods can be then compared to force methods as a way to help students understand which methods are most useful for which situations.

Studying energy early adds efficiencies to the class that are not realized with a force-centered approach. Conservation laws are among the most fundamental concepts in physics. By introducing energy conservation early in the course, students become familiar with the rules for conservation. As a result, momentum conservation and charge conservation are greatly simplified, and better understood.

Energy Often

Reorganizing and restructuring the curriculum to include an energy thread involves weaving energy considerations in with other analytic methods. In order to encourage students to utilize multiple approaches to analyze models, it is important that the approaches are studied in parallel. The existing structure separates the topics into discrete units that have little relation to each other. This structure does not encourage students to carry knowledge gained in one unit to another unit.

Treating different analytic approaches in parallel allows students to compare and contrast approaches. By explicitly comparing analytic approaches, students gain familiarity with a variety of problem solving techniques. This fosters greater coherence between analysis methods, which is a characteristic of greater expertise in physics. Furthermore, since the methods are compared, students develop intuition about which approaches are most useful in each situation, and what characteristics of situations indicate which solution method to use.

A primary difference between the energy thread curriculum and a standard curriculum is within the energy thread there is no three-week block dedicated to the study of energy. Instead, the energy unit has been redistributed throughout the entire year. This approach benefits students in two ways. First it allows the students to study forces and energy in parallel. The study of two topics in parallel is a more efficient approach, because similar situations do not need to be reestablished and studied multiple times. The second benefit is that the study of the relationships between forces and energy encourages students to look at both approaches, which also eliminates some of the need for external motivation and in turn, adds efficiency. The time gained by the study of energy and forces in parallel can then be used to include more modern topics, moving introductory physics into the twentieth century, and holding the interest of the students.

Energy Intuition

In order for students to gain expertise with energy considerations, they need to develop an intuition about appropriate use of energy analyses. The energy thread develops these intuitions by first encouraging students to use energy to analyze situations qualitatively in a variety of contexts. In order to determine which situations lend themselves to energy analyses, students must be able to recognize characteristics of these situations. The ability to qualitatively analyze situations with energy helps students recognize these characteristics quickly and effectively. Development of intuition is a slow process requiring deliberate practice and guided feed back. By treating forces and energy in parallel, the energy thread expedites that process.

As I described previously, the definition of system and choice of object model are primary constituents of the modeling strand of the energy thread. These two decisions also motivated the energy intuition segment of the design principal.

Implementation of Energy Thread Curriculum

In this section, I describe the implementation of the energy thread curriculum, including a chronological development of the key concepts in the energy thread, and the activities that fostered these concepts. To summarize the energy thread, I will first identify the central activities constituting the energy thread and then discuss the activities that support further development.

Review of Central Energy Thread Activities

In this section, I will discuss the central activities that make up the energy thread. Initially, I must describe what constitutes a central activity. As the name implies, these activities are central to the energy thread; without them, the energy thread would not exist. In order to make this list, an activity must introduce a model, a modeling tool, a new concept, develop a relationship, or emphasize an important characteristic of the energy thread. In describing these activities, I also explain their relevance to the three strands of the energy thread.

There are twenty-one activities, twelve during the first semester, nine from the second that are central, which develop the most important aspects of the energy thread. The activities from the first semester are summarized in Table 6.

Table 6

Central Activities to the Development of the Energy Thread During the First Semester

Day	Activity	Introduced
1	What is a model?	Concept of model as basis for class.
9	Ball Bounce Activity	Energy Qualitatively, Energy Pie Charts, System Schema, Extended Body Model, Gravitational Interaction Energy
16	E_{Ig} and E_k Lab	Energy Quantitatively, E_{Ig} and E_k, Energy is stored in interactions
17	E_{Ig} and E_k Lab	Equation for everything
21	Force and Energy Prob.	Comparison of Energy and Force methods
26	Force and Energy Prob.	Working as energy transfer, non-conservative system
28	Friction Lab	$E_{Internal}$ quantitatively, Force as energy transfer, Derivative and Integral relation of Force and Energy
29	$F_{Elastic}$ and $E_{Elastic}$ Lab	$E_{elastic}$
32	Universal Gravitation	$E_{Ig} = -Gm_1m_2/r$, $F_{Ig} = -dE/dr$, Gravitational interaction energy graphs as modeling tool, Energy Bar Charts
37	Collision Lab	Energy relation to momentum
39	Atomic Simulator	Microscopic Systems, E_k is related to temperature, Ideal Gasses
41	Atomic Simulator	Interparticle Interaction, Use of E vs. distance graph, Ideal Gas Law, Non-Ideal Gasses

Central Modeling Activities – First Semester

Before I begin describing the activities from the first semester, it should be noted that these many of these activities include multiple topics. This table does not indicate the amount of time spent on energy.

The first activity related to the energy thread is simple, a group discussion on the first day of class about what constitutes a model, and what models have to do with science. The intent of this discussion is to plant the seed that models are the ideal epistemological anchors to use in explaining physics and science in general.

On Day 9 the ball bounce activity introduces energy. In the ball bounce activity, students drop a rubber playground ball, and use kinematic graphs and motion maps to describe the motion of the ball. The instructor uses the process of seeding, (Desbien, 2002) or discussing with a group of students new concepts the instructor wants to introduce. Students are asked why the ball doesn't bounce as high on each subsequent bounce. This initiates a number of introductions. First, relying on the epistemological anchor that energy is related to motion, the discussion focuses on the energy of the ball. Students tend to propose the explanation that 'energy is lost'. The instructor then points out that energy is conserved. Energy being both lost and conserved, sets up a cognitive conflict which is resolved by allowing the energy to be transferred to other storage mechanisms, often the temperature of the ball is cited. At this point the instructor points out that if it is transferred to other storage mechanisms it is still within the system, although the system has yet to be chosen. Next the instructor suggests two modeling tools, the system schema in order to properly define the system being studied, and energy pie charts in order to account for the energy transfers within the system.

In the energy thread, the ball bounce activity allows for the introduction of energy as a method used to analyze situations and as a conserved quantity. Further, energy pie charts and system schema are identified as useful tools to represent the energy storage and transfer. Finally energy is used as the first causal model, prior to this activity, the class has focused on kinematics; this is the first dynamic situation they attempt to model.

In order to explain why the ball does not bounce as high, or why the ball bounces at all, they begin to invent energy storage mechanisms. Often and with guidance they invent a ball and spring model for the ball. Thus, through this simple activity, they have encountered local and global energy conservation, energy storage and transfer, representations of system and energy conservation, and extended body models. Of course, these ideas are covered at a very rudimentary level. With practice and other supporting activities, they will fill in the details of the ideas over time. Introducing them to all the details at the onset would simply overwhelm them, and usurp the value of the activity.

The ball bounce activity is the richest activity within the energy thread, a great deal is introduced all at once. In terms of the three strands of the energy thread, it plucks all three. The accounting strand leads to internal energy, and allows the explanation for the decreasing height of each bounce. The system schema and the ball and spring model of the ball come from the modeling strand. The interaction strand is represented by the energy stored in the interaction between the ball and the earth. It is rare for an activity to introduce new material to all three strands, but this is the first time the students have encountered energy in the course. The ball bounce is followed up by a number of supporting activities to encourage further interpretation of the system schema and energy pie charts.

After one and a half weeks, during which time the students would have practiced using the representational tools, they are first introduced to energy quantitatively. On day 16 they use energy pie charts to first identify the pertinent variables needed to calculate gravitational interaction energy. Discussion focuses on the effects of mass and height on gravitational interaction energy. The instructor then introduces $E_{Ig} = mgh$, and the class is able to calculate energy stored in one interaction. At that time, the class is given a lab in which they are asked to develop a form for E_k, based on any of the tools they have developed thus far. Lab groups are guided to use energy pie charts to analyze the motion of a ball falling or being thrown upward, then using microcomputer based lab equipment create graphs relating E_k to velocity. The students find that the best fit of the E_k vs. velocity graph is a quadratic fit. With this activity, quantitative energy considerations grow out of the energy pie charts and system schema, which the students are already familiar with. This demonstrates the utility of the representational tools in creating a rich model. The activity extends the practical utility of the accounting strand by finally allowing calculations based on energy. It also develops an essential component of the interaction strand, by demonstrating that gravitational energy is stored, not in objects, but that it requires an interaction.

Day 17 is a follow-up on the previous day's lab. The new tool is the equation of everything, which defines the accounting strand. During the discussion of the lab, it is emphasized that the equation of everything can be written as a direct interpretation of the energy pie charts and system schema.

On day 21, the students first analyze a situation, both from a force and from an energy perspective. They compare and contrast the analytic approaches to the problem. It is important for them to discuss the characteristics of the problem that facilitate both force and energy solution methods. One characteristic that is generally useful in determining the analytic approach is for situations with time dependence, forces are generally more useful, when the situation is lends itself to position dependant analysis, energy is generally more useful. The actual situation analyzed is not critically important, but the reflective activity of comparing solution methods is of central importance to the energy thread curriculum and the modeling strand.

Again on day 26 students encounter a problem they analyze, first with forces and then with energy. The problem itself is again not significant, but it is useful to determine the system for the students. The system should be defined such that the energy in the system is increasing. Shown in Figure 7 is the problem given during fall 2001. The system was defined as the box and the earth; the person was outside the system.

> "A person pushes a box at an angle of 45° across a smooth surface, after 4 meters, how fast is the box moving? For this problem, choose a system with the person outside of the system boundary."

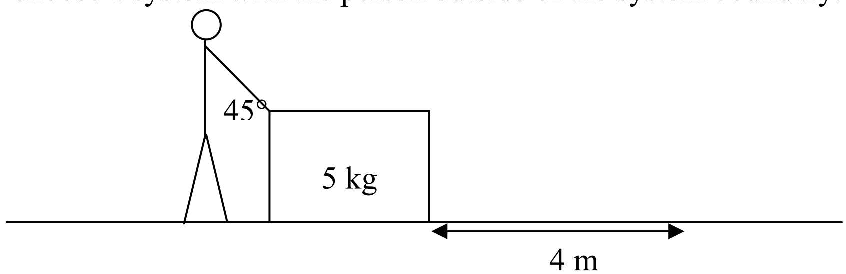


Figure 7. Problem used to introduce 'working'

The central idea of this problem is to introduce *working* as an energy transfer into or out of the system. For the first time, The First Law of Thermodynamics has a non-zero change of total energy. Local energy conservation is no longer a necessary criteria for analyzing problems with energy. Non-conservative systems can be analyzed with energy and the analysis can lead to interesting conclusions. In this problem, the conclusions are about the energy of the person pushing. By analyzing the situation first with forces, then with energy, it is possible to determine the energy the person added to the system, which is stored in the kinetic energy of the box. The force-energy problem introduces new complexity to each of the three strands, the accounting strand can now account for non-conservative systems. The modeling strand now has systems that do not include all of the objects. The interaction strand now has a tangible relationship between force and energy.

The Friction Lab, undertaken on Day 28, extends the concept of force as a way to transfer energy. In this lab, which is designed to investigate frictional forces, the relationship between force and energy is formalized. Student lab groups take data on the force required to pull a friction block at a constant speed. As a part of the students' interpretation of force data, they are led to the discovery that the negative area under the $\mathbf{F}_{friction}$ vs. **displacement** graph predicts the internal energy. In order to extend this concept, students create a graph of $E_{internal}$ vs. distance and notice the negative slope predicts the $F_{friction}$. This formal relationship is then related to the integral, and then it is posited that the negative spatial derivative of energy would yield the force, and the negative integral of force with respect to displacement would yield the internal energy. These relationships between force and energy are critical components of the interaction strand of the energy thread because they will be used to evaluate interaction energy graphs and potential graphs throughout the latter portions of the course. The relationships are developed based on the new representational tool interaction energy graph. Using representational tools to develop quantitative relationships is a characteristic of the energy thread.

Day 29 has the students develop equations for both F_{spring}, and E_{spring} through a lab activity. The development of these equations follows the reasoning developed in the friction lab from the previous day. This, again, highlights the interpretations that are possible from the representational tools. Students first take data to create a F_{spring} vs. displacement graph. Using that graph, they find the negative area under the graph to find the energy stored in the spring. The new equations are part of the modeling strand of the energy thread.

Universal gravitation is introduced on day 32; this is a challenge to both the modeling and the interaction strands of the energy thread. The existing equation associated with the model for gravitational interaction energy is $E_{Ig} = mgh$. On day 32, the students begin by making energy bar charts for a rocket that is launched from earth and ends up very far away. This leads them to the conclusion that their model for gravitational interaction energy has major discrepancies, as the rocket heads toward infinity, the E_{Ig} grows as well. In order to overcome these shortcomings, the possibility of negative energy is suggested. The students are then faced with the problem that pie charts do not represent negative energy, hence energy bar charts are introduced to represent negative energy. After the class has been exposed to bar charts, they are asked to revisit the problem that presented this problem initially. They can then explore how the possibility of negative energy allows them to maintain energy conservation.

In their initial application of energy bar charts, the students are asked what the gravitational interaction energy for the rocket earth system should be very far away from earth. To guide them, they are also asked to draw a system schema when the rocket is infinitely far away. The system schema should indicate the objects are not interacting, and therefore, the interaction energy must be zero. They are then forced to incorporate this in their bar charts, to ensure a coherent model. Once they have made a few bar charts, they are asked what a plot of E_{Ig} vs. distance would look like. This should lead them to a close relative of a -1/r shaped graph, at which time the equation $E_{Ig} = -Gm_1m_2/r$ is introduced. This line of reasoning allows the class to develop the equation for gravitational interaction energy by application and coordination of representational tools to create a model which is rich with representations.

The interpretation of this graph provides a number of new insights that become constituents of the interaction strand of the energy thread. The first interpretation of the graph is that the negative slope determines the force of gravity, emphasizing the relation between force and energy. The second interpretation of the E_{Ig} vs. distance graph was the motivation for the entire activity. E_{Ig} = mgh, is a model for gravitational interaction energy which only works in a certain region. This can be seen by looking at a graph of E_{Ig} vs. distance. The region of the graph near the surface of earth has an approximately constant slope of -mg, which is the force of gravity near earth.

The interpretations of the E_{Ig} vs. distance graph develop out of a fairly simple line of reasoning. But the contributions they make to the modeling strand of the energy thread are important. Students recognize that they must determine if they are close enough to earth to use mgh or if the inverse square law is more appropriate. It is important for them to recognize at this point, that the 'near earth' model is introduced for simplicity. Universal gravitation models do predict more accurately, but they are mathematically cumbersome and the predictive power gained is not worth the model parsimony sacrificed at this juncture in the semester. Decisions of this nature are critical to the development of models and are fundamental to the modeling strand of the energy thread. Another necessary revision of the students' understanding of energy is they are forced to accept that energy can be negative, which requires considerable effort on their part. The price of not accepting negative energy is the conservation of energy, which cannot be sacrificed. The introduction of universal gravitation and all that accompanies it, negative energy, energy bar charts and a second model for the gravitational interaction, make day 32 a challenge for students.

The 37th day of the semester brings a lab exploration on collisions. Students are asked to characterize a number of one-dimensional collisions involving lab carts. The collisions include both elastic and inelastic collisions. The primary focus of the day is to introduce them to momentum and the momentum vectors as a representational tool. The activities of the day are not centered around energy, aside from the students analyzing the collisions in terms of energy to determine the differences between elastic and inelastic collisions. The day's conclusions, however, rely on the intuitions developed through careful study of energy conservation, in that momentum is a conserved quantity like energy. This gives the class a very strong foundation for understanding momentum conservation and makes their learning much more efficient.

As the first semester draws to an end, there are two days, day 39 and day 41, which are dedicated to investigation of topics often omitted from the introductory curriculum. These two days are a benefit resulting from the efficiencies of the energy thread curriculum. During these days, the students are engaged in using *Atoms In Motion*, a computer simulation program designed to simulate the properties of matter at a molecular level. (Johnson, 2000) On day 39 the students investigate the properties of ideal gases. *Atoms in Motion* allows the user to define a number of atoms which are represented with spheres of different colors. The program also allows to either include interactions between the atoms or to only allow collisions. For the activities on ideal gases they turn off the interactions between atoms. The atoms are then set in motion. Users can add kinetic energy to the system and watch the results. *Atoms in Motion* calculates the pressure, temperature and a histogram of the kinetic energies of all atoms. By adding kinetic energy to the system, the students develop the understanding that there are relationships between kinetic energy and temperature then reconcile these relationships with the energy they had previously modeled as internal energy. Through interactions with this program, students are able to discover the relationships I have already mentioned and that ideal gases are comprised of non-interacting point particles. The discoveries made on day 39 contribute considerably to the modeling and interaction strands of the energy thread.

The activities of day 41 modify the discoveries made on day 39; again, working with *Atoms In Motion*, students turn on interactions between particles. Although the interactions are described as electrical interactions, an analogy to gravitational interactions is made, the atoms interact without touching. This is done to establish a link from the material covered during the first semester, to what will be covered in the second, where the concept of field is more prevalent. Interactions are represented on the screen by interaction energy graphs, showing an attractive tail and repulsive core, Figure 8 shows a sample of the interaction energy graph used in *Atoms In Motion*.

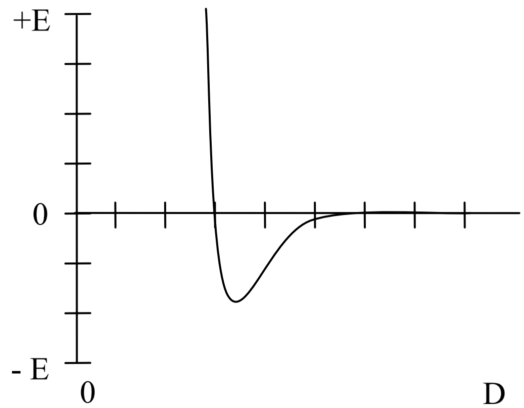


Figure 8. Representation of interaction energy graph from *Atoms In Motion*

Students are allowed to change the parameters of the interaction strength and range, which, in turn, changes the graph. Students, then, are allowed to explore. They find that the free atoms, now, are attracted to each other, and in some cases stay bonded to each other. Discussion of this process leads students to recognize this as a phase change, the gas to turns to liquid. *Atoms in Motion* allows the user to control other characteristics of the atoms and the box that contains the atoms. These controls allow students to create explanatory models for other properties of materials that for include: cohesion, thermal expansion, condensation, and compressibility. One control allows students to make the floor of the box conduct heat, then atoms that hit the floor have kinetic energy removed, which leads to condensation. A built in simulation includes a model of a solid, all the atoms are bound together at a very low temperature, adding kinetic energy to the atoms slowly first shows the solid expanding, then melting and eventually evaporating.

Day 41 is important because it encompasses topics the students have learned throughout the entire semester, kinematics of the molecules, energy of the interactions and the molecules, force and momentum from the collisions and how to coordinate all these analytic methods. Furthermore, it allows students a first chance to explore more modern physics, including topics that ABET 2001, and the Department of Education (ABET, 2001), (NRC, 1995) have identified as important topics for science classes. These activities prepare the students for second semester, linking the mechanics of the first semester to the interactions that comprise the bulk of the second semester. This connectivity is fundamental to the energy thread, especially the modeling and interaction strands.

Central Modeling Activities - Second Semester

The central activities of the second semester begin with electrical interactions, which students recognize from the *Atoms In Motion* activities at the end of the first semester. A summary of the central activities to the energy thread curriculum from the second semester is shown in Table 7.

Table 7

Central Energy Thread Activities, Second Semester

Day	Activity	Introduces
2	Sticky Tape Activity	Interactions between charged particles
6	Calculation of E_{Ie} prob.	Energy stored in electric interaction, $E_{Ie} = kQ_1Q_2/r$
14	Electric Interactions Problem	Energy stored in electric field
16	Potential Modeling	Introduction to potential, V
18	Equipotential Modeling	Introduction to equipotentials, -dV/dr = Electric Field
36	Ampere's Law	Relationship between B and V
40	Models of Changing Fields	Introduction to radiation as energy transfer,
41	Maxwell's Equations	Light as a form of radiation

The central activities of the second semester often parallel and draw upon the activities from the first semester. Occasionally, they are reinterpretations of the relationships developed during the first semester, applied to electric fields. They are, however, the basis for cementing connections between force and energy which makes them central to the energy thread curriculum.

The second semester begins with student investigation of the interactions between electrostatically charged tapes. This investigation follows Chapter 1 in Electric and Magnetic Interactions (Chabay Sherwood, 1995). In this investigation, students model the interactions between tapes as electrical in nature. The cause of these interactions is charged particles, electrons and protons. This activity builds on the modeling strand, in which the size scale is radically different than the scale they were accustomed to during the first semester. The models created during the second semester must take into account the differences in size and energy.

Day 6 introduces electric interaction energy, both qualitatively and quantitatively. The activities on day 6 begin with a comparison of the moon orbiting around the earth, and an electron orbiting the nucleus. An analogy between these two systems helps develop the details of electric interactions, two charged particles, and the distance dependence. After comparing the differences, the similarities are highlighted and the discussion ends with the introduction of $E_{Ie} = kQ_1Q_2/r$. This begins the study of electric interactions from an energy standpoint. Students are reminded that the negative slope of an interaction energy graph gives the force, which in this case is Coulombs Law. This exemplifies the type of activity that develops the interaction strand of the energy thread.

In order to explore the utility of the electric interaction energy graphs, they are used to create an explanatory model for the differences between conductors and insulators. Students are shown three graphs, one with a steep slope, one with a shallow slope and one with an intermediate slope. They are then asked to predict and explain which one is most likely to conduct, and which one is most likely an insulator. Insulators exert a greater attractive force on the valence electrons, which is represented by a steeper slope on an interaction energy graph. This activity again demonstrates how modeling tools can be interpreted to generate quantitative relationships, which is typical of the modeling strand of the energy thread.

The 14th day of the second semester the class revisits an activity similar to Day 32 from the first semester. Again, the students are asked to use energy to model two charges separated by significant distance. They, again, find that energy bar charts are the modeling tool of choice, because they can represent negative energy. Although the discoveries from Day 14 are not novel, they are important because they are applied to electric fields. The analogous reasoning made possible by the parallels between gravitational fields and electric fields is an important component of the interaction strand of the energy thread.

Day 16 from the second semester of the energy thread curriculum involves activities that are familiar to the students. In fact, the students again analyze the interaction between two like charges as one charge moves in from far away. The same situation is used because the students have already analyzed the situation, they already command a developed set of interpretations of the situation. The benefit is that students can immediately relate newly introduced material to material they already understand. Creating connections in students' understanding is aided by the repeated analysis of similar situations, which is a primary goal of the energy thread.

The new concept introduced on Day 16 is potential. It is introduced in relation to the change in energy between two charges. Potential is further justified as a useful quantity by the extension of the interaction energy of many particle systems. Again, the analogy to gravitational potential is drawn, connecting situations in different contexts that can be analyzed with the same tools and modeling approaches. Introducing potential makes a novel contribution to the interaction strand; previously, interactions required two objects. With potential, the interaction being described has not been actualized, instead, it is the possibility for an interaction.

On day 18, two new modeling tools are introduced. Using the program *EMField*, students are encouraged to investigate equipotentials. (Trowbridge and Sherwood, 1996)

EMField is a simulation that has the ability to draw field lines, field vectors, and equipotential surfaces for discreet charge distributions. It is an extremely useful software package within the energy thread, because it allows the class to explore equipotentials and the relationship between equipotentials and electric fields quickly and in a qualitative manner.

The class explores equipotential surfaces in the following manner; with a single point charge as the source, they create equipotentials at evenly spaced ΔV. Once they have this equipotential surface, they are asked to create a potential graph. In this way equipotentials and potential graphs are introduced. Once they have made the graphs, the students are asked to interpret the models, and are led to the conclusions that like interaction energy graphs, the negative slope of a potential graph gives the value of the field. This conclusion closes the circle of interaction descriptions; potential, interaction energy, force and field all are related explicitly. The connections are all related directly to the modeling tools used to represent each of the quantities. At this point, the students have the tools necessary to model most all situations that are commonly found in the introductory curriculum. The remaining central activities relate to inferences made directly from the modeling tools they already have developed and the coordination of those representations.

Later in the second semester, on Day 36, students again encounter a central activity in the energy thread curriculum. This is the day they encounter Faraday's Law. The students are provided a number of coils of wire, two strong magnets and an analog Galvanometer, and asked to explore the important criteria for describing the induced potential. The instructor suggests the students pass the magnet through the coils, then repeat quickly or slowly. The discussion of this lab exploration arrives at the conclusion that changing magnetic flux induces a potential in the coils. This suggests a relationship which does not have a mechanical analog, a changing magnetic field induces an electric field. This is an important characteristic of the interaction strand of the energy thread, as it establishes a mechanism for radiation.

The last two days of the second semester, Days 40 and 41, introduce radiation as an energy transfer. This completes the equation of everything, ΔE = Working + Heating + Radiating. Students create energy bar charts to describe the following situation: a person moves a positively charged particle up and down while a second positive charge is fixed in a stationary position 3 meters away, consider the two charged particles to be the system. The energy entering the system from the person moving the charge must leave the system through some other means. When this conclusion is coordinated with the knowledge that changing electric fields create magnetic fields, the students are led to propose that the changing fields radiate the energy away. This conclusion is in line with their earlier deduction that fields store energy. Though the details are omitted, the students then have the basis to explain light as an energy transfer mechanism. In this manner, the energy thread is wrapped up; ending with the coordination of a number of inferences from models the students had created. The inferences were always made in terms of models and guided by energy analysis.

Design of the energy thread intended that the repeated creation and interpretation of models using energy would develop models as the epistemological anchors for a physics class, and energy as an ideal epistemological resource that unifies the topics within the curriculum.

Although this activity concludes the set of essential activities within the energy thread curriculum as it presently exists, it is still designed to establish connections with a third semester of physics, in which optics, the interaction of light and matter, and quantum mechanics could be covered.

Supporting Activities

Whereas supporting activities enforce, reexamine and provide practice or review of material already covered, they comprise an essential portion of the energy thread curriculum. Gaining expertise at using modeling tools, creating and interpreting models and determining the utility of the modeling tools is a critical component of the energy thread. Although no single support activity is crucial to the implementation of the energy thread curriculum, the group of supporting activities is essential to the development of the energy thread. Table 8 describes the first semester activities that support the energy thread as it has been implemented. Table 9 describes the activities from the second semester.

Table 8

Supporting Activities in the Energy Thread Curriculum, First Semester

Day	Activity	Purpose
11	Energy Pie Charts	Practice system definition, practice using energy pie charts
12	2-d Motion Problem	Coordinate energy representations with Kinematics Modeling Tools
18	Skateboarder Problem	Energy pie charts and system must agree with quantitative representations, Coordination of modeling tools
23	Atwood’s Machine Prob.	Comparison of force and energy analytic methods for constant force
31	Spring Problem	Comparison of force and energy analytic methods for variable force
34	Escape Velocity Prob.	Energy conservation and Interaction energy graphs
38	Impulse and Explosion Problems	Coordination of momentum and energy representations, Definition of system is critical

Table 9

Supporting Activities in the Energy Thread Curriculum, Second Semester

Day	Activity	Purpose
7	Circuit Lab	Introduce Voltage in circuits
8	Path of electron around a circuit	Use Conservation of Energy to deduce Kirchoff's Loop Rule
9	Path of electron around a circuit	Practice Energy Bar Charts, Kirchoff's Loop Rule
11	Circuit Lab	Use of energy bar charts to deduce power
17	Potential Integrals	Potentials add like energy, potential of continuous charge distribution
19	Equipotential Problem	Coordination of representational tools, force, field, interaction energy, potential, equipotential
29	Capacitors in Circuits	Energy bar charts to deduce energy stored in a capacitor
30	Capacitors in Circuits	Relate energy stored in capacitor to Kirchoff's Loop Rule

Review of Implementation of the Energy Thread

Via the preceding activities, the energy thread is propagated throughout the curriculum. The above tables can be interpreted in a number of ways. It is important to compare the activities included in the energy thread with the stated design principles of the energy thread. One principle is that energy should be introduced early, and often. During the first semester energy is first introduced in the third week of classes, prior to forces, and earlier than in the standard curriculum. Over the course of the year, there are 36 activities listed as either central to or supporting the energy thread. This means energy considerations are employed on 40% of the days of the semester. In comparison the standard treatment of energy includes a three-week coverage of energy each semester, yielding only 20% of the days. This begs the question, "Is the time spent on energy significantly different in the two curricula?" The answer is not significantly. Although energy considerations are employed on 40% of the days, on many of those days, energy was being considered in parallel with another analytic method, which drastically reduces the amount of time spent exclusively on energy analyses. Table 10 outlines the activities that are listed as energy activities in the energy thread curriculum, but are activities where energy is considered in parallel with another topic.

Table 10

Energy Thread Activities Serving Dual Purpose, Energy and Other Topic

Semester and Day	Activity	Topics
Semester 1 Day 1	What is a model?	Nature of Science
Day 11	2-d motion problem	Kinematics and Energy
Day 21	Force and Energy Problem	Force and Energy
Day 23	Atwood's Machine	Force and Energy
Day 26	Working Problem	Force and Energy
Day 28	Friction Lab	Force and Energy
Day 29	Spring Lab	Force and Energy
Day 31	Spring Problem	Force and Energy
Day 37	Collision Lab	Momentum and Energy
Day 38	Impulse and Explosion Problems	Force, Momentum and Energy
Semester 1, Day 2	Sticky Tape Activity	Force and Energy
Day 14	Electric Interactions Problem	Energy and Field
Day 19	Equipotential Problem	Potential and Energy
Day 29	Capacitors in Circuits	Energy and Field
Day 30	Capacitors in Circuits	Energy, Field and Potential
Day 36	Ampere's Law	Magnetic Field, Potential and Energy
Day 40	Models of Changing Fields	Electric, Magnetic Fields and Energy
Day 41	Maxwell's Equations	Electric, Magnetic Fields and Energy

As can be seen in Table 10, a number of activities serve dual purpose between energy and other topics. The estimate that 40% of class time is over exaggerated, it is more realistically approximately 20-25% of the time on energy concepts, which is congruent with the amount of time spent traditionally on energy.

Chapter Five

Data and Analysis

In this chapter I will report the data collected and analyze said data. The quantitative data collected provides a context for the interview data; as a result, I will report and analyze it first. The interview data requires an in-depth analysis, which follows.

Quantitative Data Collection

As with any study that involves comparison groups, there are difficulties in collecting the data, these difficulties are exacerbated when the comparison groups are 3000 miles apart. In my initial design, the SCALE-UP and FIPE groups were to have been compared on a number of instruments and problems. There were difficulties in collecting data at North Carolina State University during the second semester. No data was collected during the Electricity and Magnetism portion of the course. However, the instructors of the SCALE-UP project have been kind enough to furnish data from the Mechanics portion of the course. In this chapter the comparisons will be based on Mechanics only, the rest of the quantitative data will be derived from ASU's FIPE program and will be forced to stand alone.

A main reason the particular comparison groups in this study were chosen was due to the similarity in class size. As it turned out, however, the two classes were not the same size. During the first semester there was a severe lack of enrollment in the FIPE program; only 45 students enrolled, compared to 66 during the previous year. The FIPE enrollment shrank further during the second semester with only 27 students signing up. Although the number of students is low, the comparisons are only possible for first semester when enrollment was higher. Accordingly, I have proceeded with the analyses described in Chapter Three.

Force Concept Inventory Data

There were two reasons for including the FCI. The first was to establish that the students entering the two courses were approximately equivalent. The second was to ensure that by including the energy thread, the coverage of forces was not compromised. Pretest and posttest scores from the two courses can be seen below in Table 10. As can be seen in Table 11, these two classes, which have traditionally been very similar with respect to FCI pretest and posttest scores, seem to be quite different this year. An independent samples t-test was conducted on the pretest, posttest, and gain scores. The pretest class means are significantly different at the 0.01 level, $t(117) = 4.196$, $p < .000$ (two-tailed). Because there are significant differences between the groups on the pretest scores, any comparisons between groups should be viewed with caution. The posttest scores are also different at the 0.01 level, $t(117) = 3.274$, $p < .001$(two-tailed). The mean Hake gains, however, are not significantly different, $t(117) = 1.397$, $p = .165$(two-tailed). The outcome of the FCI data is that the initial assumption that the groups were roughly equivalent is invalid. Even though the posttest means were significantly different, the data does not indicate that the FIPE group received a lesser treatment of force concepts. The FIPE group had a higher posttest score, and showed higher gains, therefore taking a minimal view, at least the FIPE students received a reasonable treatment of force concepts.

Table 11

Force Concept Inventory Pre, Post and Gain Scores

	SCALE-UP	FIPE
FCI Pretest Score	36.8 ± 17.4%	50.6 ± 19.6%
FCI Posttest Score	58.4 ± 17.2%	70.5 ± 20.4%
Gain	0.26 ± 0.46	0.38 ± 0.31

Conceptual Survey in Electricity and Magnetism Data

Comparisons to the SCALE-UP program are not possible on the CSEM, but the FIPE data is nevertheless important. The CSEM pretest, posttest and gain scores can be found below in Table 12. The CSEM data is in line with the published results. For calculus-based university physics classes, Maloney et al. found posttest average of 47± 16%. The score of 52.6% is disappointingly low for the FIPE, one would hope the improved understanding of potential would have corresponded to higher CSEM scores. Minimally, the FIPE class did a comparatively adequate job on electricity and magnetism concepts. Two aspects of the CSEM may have played a role in the poor performance of the FIPE students, first is the number of questions on the CSEM that relate directly to the energy thread is a small portion of the total score on the CSEM. Also the CSEM has a KR-20 reliability of 0.75, which is lower than any of the other standard instruments, which suggest the CSEM requires some modification which is beyond the scope of this study.

Table 12

Conceptual Survey in Electricity and Magnetism Pre, Post and Gain Scores

	FIPE
CSEM Pretest	26.5 ± 10.4%
CSEM Posttest	52.6 ± 18.0%
CSEM Gain	0.39 ± 0.18

Rate and Potential Test Data

Results from the RAPT provided motivation for a more in-depth study of the energy thread curriculum. Rhett Allain reported results from the 2000-01 SCALE-UP class of 55.9%. (2001) The FIPE average from the 2001-02 year was 64.7 ± 21.9%. Because results from the 2001-02 SCALE-UP class are not available, the FIPE scores from 2001-02 class are significantly different than the 2000-01 SCALE-UP scores. Of course this comparison does not hold for this year's SCALE-UP data, but it is suggestive that a similar relationship might hold.

The difference in scores on the RAPT has been attributed to an improved understanding of potential. The energy thread explicitly motivates the concept of potential through energy arguments. As a result, the students do not see potential as an imposed concept. Also, because the representations used with potential are closely related to the representations used for potential energy, there can be a transfer of understanding from one concept to another. Although RAPT data seems to suggest benefits of including an energy thread, it remains difficult to interpret RAPT data due to the lack of comparative data and relative shortage of baseline data. In future studies, this data could possibly become more valuable and interpretable.

Common Exam Problem Data

Data from standard instruments such as the FCI, CSEM, and RAPT are interesting, however, they do not address students' approaches to or success at solving problems. Common exam problems provide an interesting look at how the energy threaded instruction impacted students in this regard. Initially, the problems were scored by two physicists based on the rubric described in Chapter Three. The scores from the two raters were correlated in order to establish a measurement of interrater reliability. The correlation coefficients measured were $r = 0.78$ for problem #1, $r = 0.78$ for problem #2, $r = 0.75$ for problem #3, $r = 0.80$ for problem #4. This shows the scores for the two raters were correlated, so the rubric provides reliable data. These correlations are not as strong as often is expected in interrater reliability, future studies will involve more practice and communication to improve interrater reliability.

The scores from the problem solutions can be found in Table 13 shown below. In order to establish differences between the class means, independent samples t-tests were performed on the scores from problems 1 and 2. The class means on both Problem #1 and Problem #2 were significantly different at the .01 level, Problem #1, $t(135) = 7.138$, $p < .000$(two-tailed) and Problem #2, $t(134) = 6.290$, $p < .000$(two-tailed). Because the scoring rubric was designed to assess the initial analysis of problems, the use of representations and the extraction of information from the representations, it can be concluded from these comparisons that the two classes are different in respect to these variables. To support this conclusion each of the two problems have been subjected to a rigorous analysis individually. First I present the analysis of Problem #1.

Table 13

Problem Solving Scores from the FIPE and SCALE-UP

	FIPE	SCALE-UP
Problem #1, Mechanics	4.56 ± 1.81	2.56 ± 1.36
Problem #2, Mechanics	3.56 ± 1.74	1.94 ± 1.21
Problem #3, E&M	4.26 ± 1.31	-
Problem #4, E&M	4.30 ± 1.98	-

Common Exam Problem #1 Analysis

The differences in total score between the FIPE and the SCALE-UP class can be seen in the distribution of solutions shown in Figure 9. As can be seen, the FIPE scores are shifted further to the right, indicating a more extensive use of qualitative analysis, representation, extraction of information and reflection. The energy thread curriculum was designed to address these specific characteristics of students' problem solving approach, with this in mind a general conclusion is that the energy thread was successful at engaging students in the use of representational tools to analyze situations and extract information from the situation.

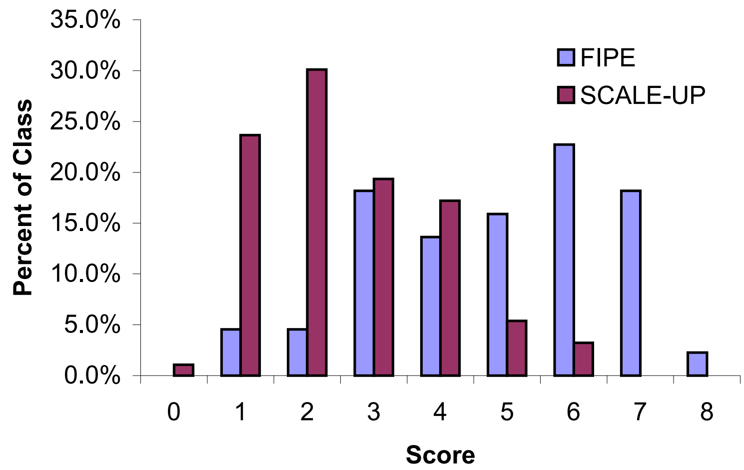


Figure 9. Distribution of FIPE and SCALE-UP scores on Common Exam Problem #1

From the comparative data on problem solving, a second question can be asked, while the classes differ on the use of representations and analysis, does this relate to more successful problem solving? In order to address this question, the problem solving data has been analyzed in a second manner. As described in Chapter Three, the problems were characterized as either correct or incorrect. The problem solving data was then recoded in order to define two new groups: the students who correctly solved the problem, and those who did not. Before the new groups could be compared on the problem score, the data had to be slightly modified. In the original rubric, the total score was computed, which included points for correct extraction of information from the representations. Students who did not solve the problem correctly, would not have earned points in this category. A new score was computed this time using only the Initial Analysis, Represent and Organize sections of the scoring rubric. This was done so the extraction of information data was not counted twice. These new scores are referred to as the Represent and Analyze scores. The Represent and Analyze scores were then compared based on the new grouping of correct or incorrect. The distribution of the Represent and Analyze scores is shown in Figure 10.

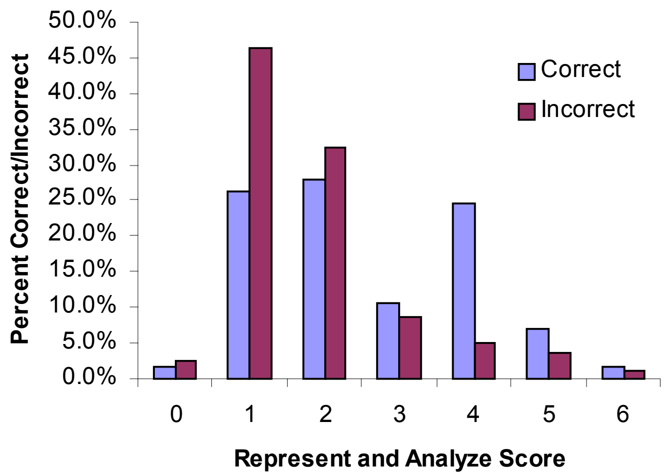


Figure 10. Distribution of Represent and Analyze scores on Common Exam Problem #1

The distribution of scores for this problem indicates that many students had a solution method, since most students had a score of 2 or more, this indicates they went beyond the analysis of the situation and created at least one valid representation. The majority of students who did not correctly solve the problem had Represent and Analyze scores of 1 or 2, very few had scores of 3 or greater. Similarly, over 50% of the students who correctly solved the problem had scores of 1 or 2, but another 25% had scores of 4. Initially, this may seem to contradict the conclusion that students who analyze and represent the problem have greater success at solving the problem. After reviewing this data, I recognized that Problem #1 was a very simple one step problem, which requires only simple solutions that could be created without further representation. The students who solved the problem correctly may have only needed 1-2 representations to sufficiently analyze the situation. The students who did not correctly solve the problem could have made mathematical errors. The mean scores, when subjected to an independent samples t-test, did show significant difference at the .01 level, $t(135) = 3.334$, $p = .001$(two-tailed). The Represent and Analyze scores can be found in Table 14.

Table 14

Represent and Analyze Scores Grouped by Correct/Incorrect

	Correct	Incorrect
Problem #1	2.46 ± 1.33	1.77 ± 1.09

Common Exam Problem #2 Analysis

The second problem was significantly more difficult than the first problem. Solving Problem #2 involved at least two steps, whereas the first problem required only one. As a result a greater number of representations can be useful in the creation of a solution. As shown in Figure 11, the distribution of total scores represents a more pronounced difference between the two classes. The FIPE class is an approximately normal distribution centered around 4, whereas the SCALE-UP scores are skewed to the left, with 1 being the most common score. The differences in total score between the two classes, which is shown in Table 14, is significant at the .01 level, $t(134) = 6.290$, $p < .000$(two-tailed).

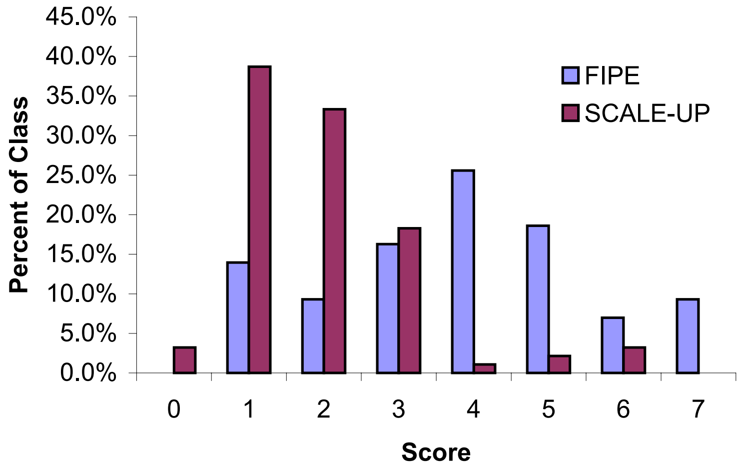


Figure 11. Distribution of FIPE and SCALE-UP scores on Common Exam Problem #2

When the problem solutions were grouped as correct/incorrect, the differences in the Represent and Analyze scores were exaggerated as seen in Figure 12. Again, according to an independent samples t-test, the differences in mean Represent and Analyze scores are significantly different for the correct and incorrect groups, t(134) = 5.078, p < .000(two-tailed).

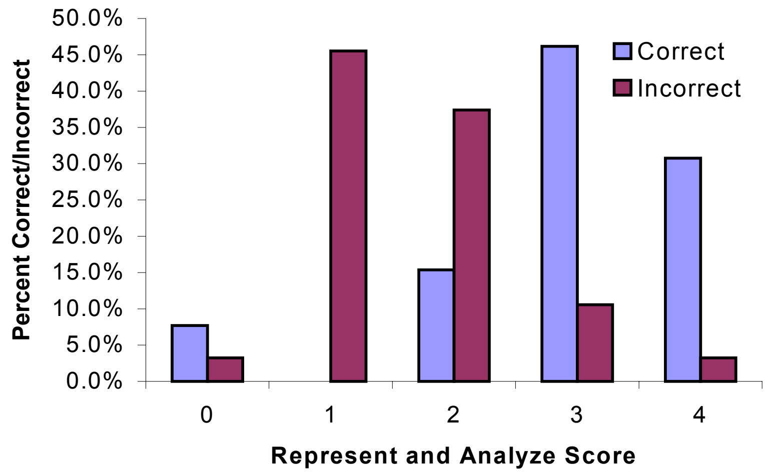


Figure 12. Distribution of Representation and Analysis Scores on Common Exam Problem #2

The results from Problem #2, which was more difficult than Problem #1, showed that the students that correctly solved Problem #2 did a better job of analyzing and representing the problem. The majority of students with correct solutions scored 3 or 4, and the majority of students with incorrect solutions, scored 1 or 2. The conclusion derived from this, is that on complex problems, more representation and analysis seems to be of greater utility in constructing a correct solution. This explanation is a powerful reason for including an energy thread into the curriculum to introduce a greater variety of representational tools.

Common Exam Problem #3 Analysis

Although the SCALE-UP class did not administer the third and fourth common problems, the data from the FIPE course is of interest. Unfortunately, during the second semester, the FIPE class was significantly smaller than during the first semester. The total number of students shrunk to 27. A consequence of this is when the class is split into two groups, the size of the groups is too small to use standard t-tests, and so the analysis of these two problems is more descriptive. Also, since there is no comparison group, there is no reference point for the data. Figure 13 illustrates the distribution of total scores for Problem #3.

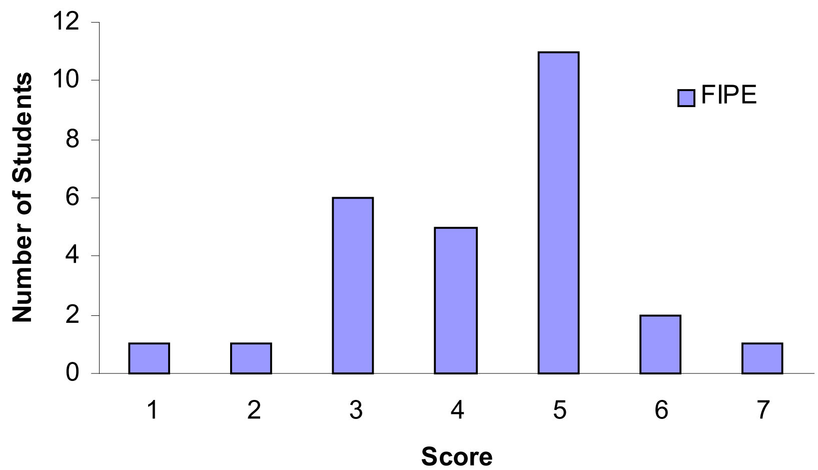


Figure 13. Distribution of scores from FIPE on Common Exam Problem #3

By inspecting the distribution of total score, two conclusions can be drawn, first that all students can make an attempt at solving the problem. All but two students achieved a score of at least 3, which indicates uniformly, they were able to create some representations, analyze the situation, or extract information about the situation. Students in the FIPE cannot make the common claim, 'I didn't know where to start.' Since the majority of students achieved a score of at least 5 it can be said that the energy thread curriculum has encouraged these students to analyze situations, and create representations which have been shown to be helpful in solving problems. This is one of the characteristics of expert physicists, the energy thread curriculum is designed to encourage.

Common Exam Problem #4 Analysis

The data from Problem #4 is interesting because of the outliers in the data. The distribution of total scores is represented in Figure 14. Students, once again, demonstrated an ability to *start* the problem as can be seen that the lowest score was 1. The highest score of 11 was earned when a student, after questioning the answer initially obtained by using energy methods, solved the problem again with force methods as a way to check his work. A copy of this students' solution can be seen in Figure 15 a and b.

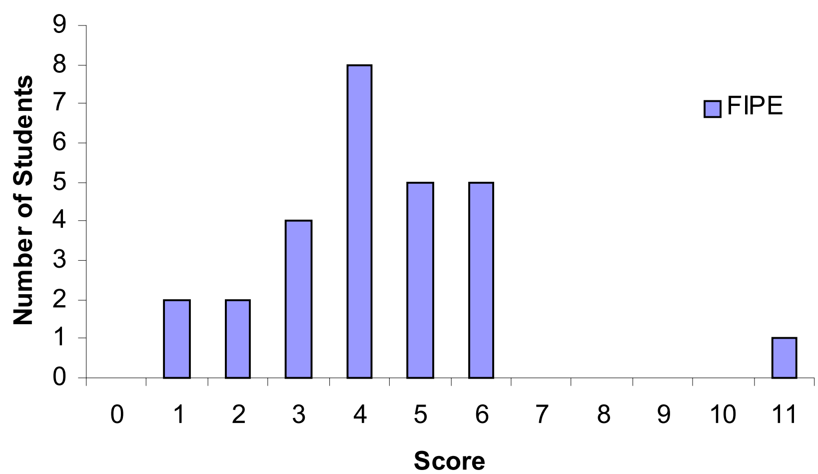
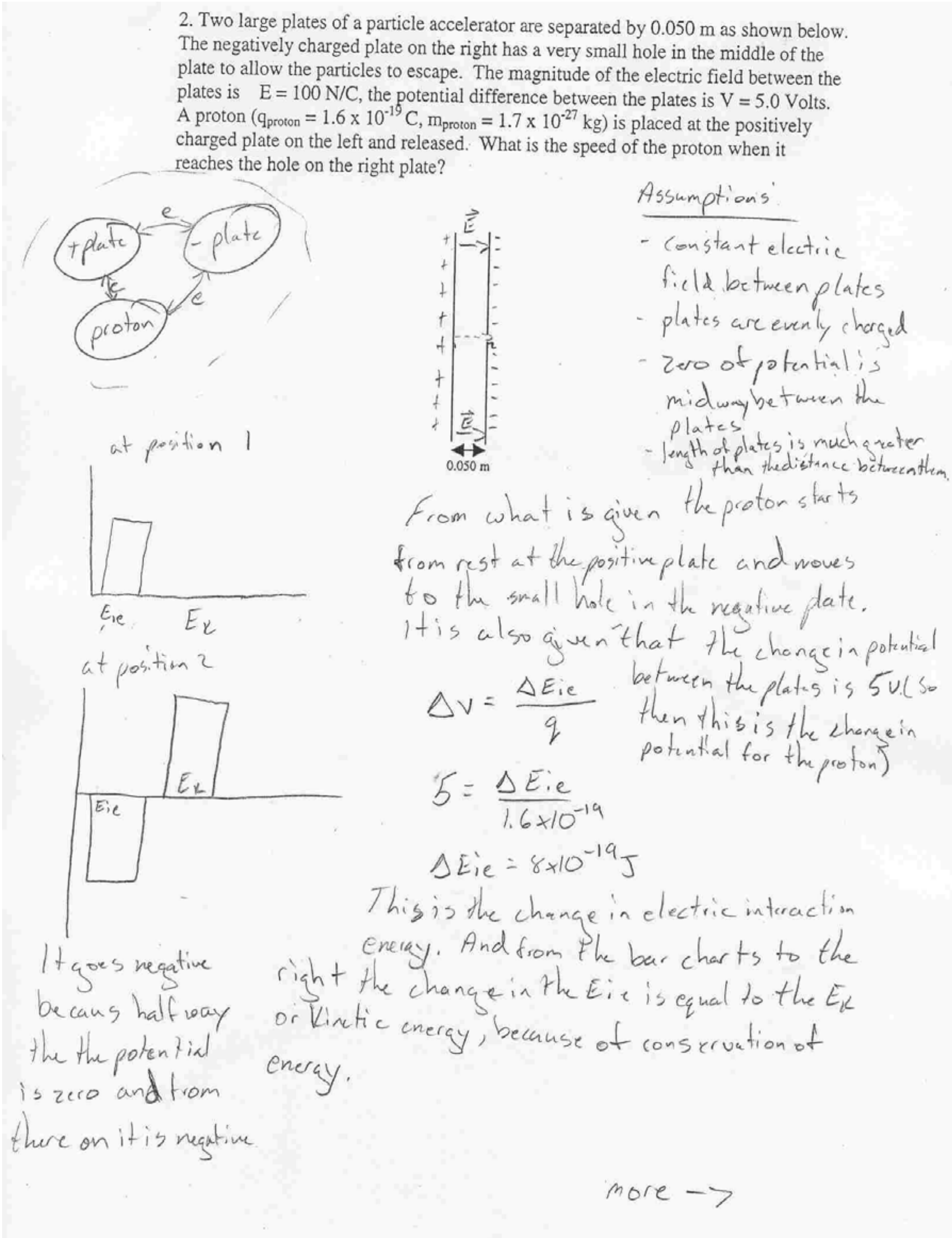


Figure 14. Distribution of scores from FIPE on Common Exam Problem #4



2. Two large plates of a particle accelerator are separated by 0.050 m as shown below. The negatively charged plate on the right has a very small hole in the middle of the plate to allow the particles to escape. The magnitude of the electric field between the plates is E = 100 N/C, the potential difference between the plates is V = 5.0 Volts. A proton ($q_{proton} = 1.6 \times 10^{-19}$ C, $m_{proton} = 1.7 \times 10^{-27}$ kg) is placed at the positively charged plate on the left and released. What is the speed of the proton when it reaches the hole on the right plate?

Assumptions:
- constant electric field between plates
- plates are evenly charged
- zero of potential is midway between the plates
- length of plates is much greater than the distance between them.

From what is given the proton starts from rest at the positive plate and moves to the small hole in the negative plate. It is also given that the change in potential between the plates is 5V (so then this is the change in potential for the proton)

$$\Delta V = \frac{\Delta E_{ie}}{q}$$

$$5 = \frac{\Delta E_{ie}}{1.6 \times 10^{-19}}$$

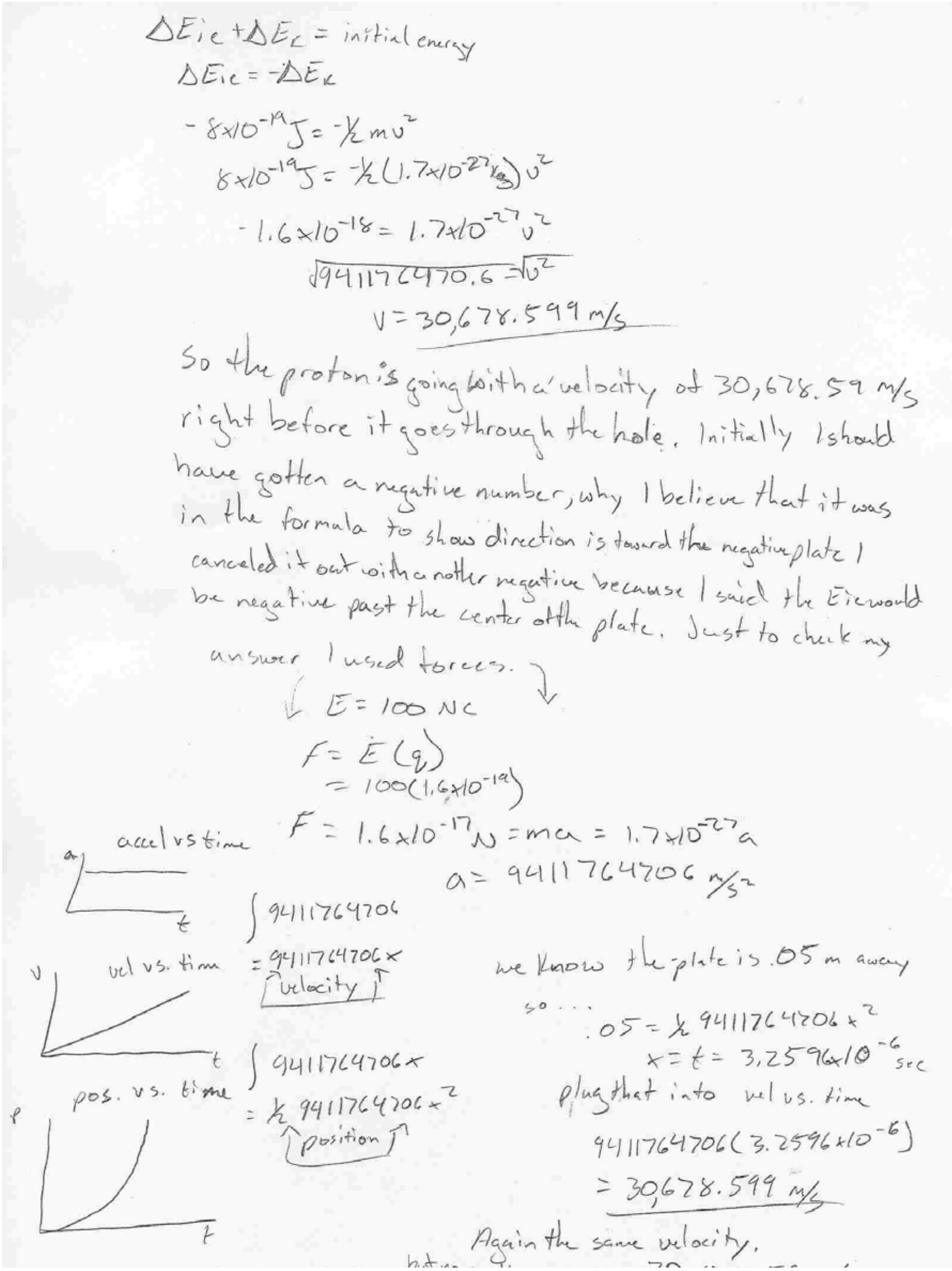
$$\Delta E_{ie} = 8 \times 10^{-19} J$$

This is the change in electric interaction energy. And from the bar charts to the right the change in the Eie is equal to the Ek or kinetic energy, because of conservation of energy.

It goes negative because half way the the potential is zero and from there on it is negative

more →

Figure 15a. Page one of Student #19's exemplary solution



$\Delta E_{ic} + \Delta E_{k}$ = initial energy

$\Delta E_{ic} = -\Delta E_{k}$

$-8\times10^{-19} J = -\frac{1}{2} m v^2$

$8\times10^{-19} J = -\frac{1}{2}(1.7\times10^{-27} kg) v^2$

$-1.6\times10^{-18} = 1.7\times10^{-27} v^2$

$\sqrt{941176470.6} = \sqrt{v^2}$

$v = 30,678.599\ m/s$

So the proton is going with a velocity of 30,678.59 m/s right before it goes through the hole. Initially I should have gotten a negative number, why I believe that it was in the formula to show direction is toward the negative plate I canceled it out with another negative because I said the Eic would be negative past the center of the plate. Just to check my answer I used forces.

$E = 100\ NC$

$F = E(q)$

$= 100(1.6\times10^{-19})$

$F = 1.6\times10^{-17} N = ma = 1.7\times10^{-27} a$

$a = 9411764706\ m/s^2$

accel vs time

$\int 9411764706$

$= 9411764706x$

velocity

vel vs. time

$\int 9411764706x$

$= \frac{1}{2} 9411764706x^2$

position

pos. vs. time

we know the plate is .05 m away so...

$.05 = \frac{1}{2} 9411764706x^2$

$x = t = 3.2596\times10^{-6}$ sec

plug that into vel vs. time

$9411764706(3.2596\times10^{-6})$

$= 30,678.599\ m/s$

Again the same velocity.

Figure 15b. Page two of Student #19s' solution to Problem #4

The solution, shown in Figure 15 a and b, is an outstanding example of the type of solution that is encouraged by the energy thread curriculum. The student has used a number of representational tools, and has coordinated an energy approach with a force approach to solving the problem. The coordination of approaches convinced the student that the problem had been solved correctly and the answer was appropriate.

Closer Look at Student #19

Because the problem solution was such an outstanding example of the type of solution encouraged by the energy thread, I probed further, looking back at the other data available for the student, who will be referred to as Student #19. The summary of data on this student is available in Table 15.

Table 15

Related Data on Student #19

Instrument	Score
FCI Pre	40%
FCI Post	66.7%
CSEM Pre	6.3%
CSEM Post	65.6%
RAPT	64%
Problem #1	6 (Incorrect)
Problem #2	6 (Correct)
Problem #3	5 (Correct)

Looking at the data on this individual student, it is evident that this student did not enter the class with any particular advantage, with an average score on the Pre FCI, and a far below average Pre CSEM score. Student #19 routinely analyzed situations, and made use of the representational tools as is evident by his scores from the three comparison problems, all of which are above average. Furthermore, this student has made significant gains both on the FCI and more pronouncedly on the CSEM. Student #19 seems to have excelled in the energy thread curriculum, the student made productive use of the representational tools, and made substantial gains as a result.

Problem Solving Approach Analysis

The final analysis of the Common Exam Problems conducted was to analyze the primary solution method employed by the students. To do this, two physicists categorized the problem solution methods for all solutions. The data was then compared and when differences of opinion occurred, they discussed and came to a consensus. The characterization was recorded and tabulated. The data can be seen in Tables 16 and 17.

Table 16

Problem #1 Data, Organized by Solution Approach

	FIPE		SCALE-UP	
Number of Students	44		93	
Percent Correct Solutions	50.0%		37.6%	
Percent Using Force Approach (Percent Correct)	63.6%	(42.9%)	77.4%	(43.1%)
Percent Using Energy Approach (Percent Correct)	31.8%	(71.4%)	7.5%	(57.1%)
Undetermined Approach	4.6%		15.1%	

On Problem #1, either force or energy approaches were appropriate choices. The two classes have somewhat distinct characteristics as far as problem solving approach is concerned. The FIPE has a lower percentage using force approaches than the SCALE-UP group. Interestingly, the proportion of students who used force approaches to correctly solve the problem is identical in each class. FIPE students employed energy approaches much more frequently than SCALE-UP students did. One of the expected outcomes of the energy thread curriculum is that students will employ a greater variety of problem solving approaches and it is certainly the case with this problem. Students in the energy thread are not reliant solely on force methods, they also are comfortable with energy approaches because energy has been a focus from the beginning of the course.

All students that used an energy approach solved Problem #1 more effectively than those that used force approaches. The force approach requires use of vector methods, and the recognition that the acceleration and velocity are in opposite directions, the energy approach does not require these distinctions. These differences in ease of solution contribute to the differences in success rates between the two approaches. The FIPE students who chose an energy approach had a greater success rate of solving the problem than the SCALE-UP students who used an energy approach. A plausible explanation for this is that the energy representational tools available to the FIPE students guided them to a correct solution, and the SCALE-UP students were not familiar with these modeling tools.

Table 17

Problem #2 Data Organized by Solution Method

	FIPE	SCALE-UP
Number of Students	43	93
Percent Correct Solutions	20.9%	4.3%
Force Approach	16.3%	45.2%
Energy Approach	69.8%	30.1%
Kinematics Approach	0.0%	2.2%
Undetermined Approach	14.0%	22.6%

Problem #2, as I have said, was more difficult. The number of students correctly solving the problem indicates the difficulty of the problem. Problem #2 required use of energy approaches; analyzing the situation with forces does not lead to a solution. I hypothesized that students in a force-centered curriculum would attempt to use force approaches even when forces did not lead to problem solutions. The data from this problem bears out this hypothesis. Students in the energy thread curriculum were much more likely to recognize that forces were an inappropriate solution approach and as a result, employed an appropriate energy approach. The SCALE-UP students were 3 times as likely to employ force approaches as the FIPE students. This leads to the conclusion that the energy thread was effective in enabling students to identify and utilize appropriate problem solving approaches.

From the comparative data, a number of conclusions can be drawn. To paraphrase the Hippocratic Oath, ‘First, do no harm.’ Inclusion of an energy thread at least does no harm. As can be seen in FCI and CSEM scores, students’ understanding of force or electricity and magnetism concepts have not been compromised in favor of energy concepts. In fact, the data I have presented suggests that the inclusion of the energy thread can reap substantial benefits in terms of the understanding of energy concepts, ability to identify appropriate uses of energy considerations and the ability to apply energy considerations in solving problems by qualitatively analyzing situations and creating representations that allow them to extract information from the situations. These conclusions are significant, and can be further supported by the interview data collected.

Focus Group Interview Data

Interview data has a high information density, and tends to be scattered. The best way to approach the interview data is by limiting the scope of the analysis. I have identified a number of characteristics, which will be addressed in the analysis of the interview data. Students' responses characteristically indicated development of thinking about energy concepts, specifically, understanding of conservation principals, and notions about the nature of energy. The interviews were structured to elicit these themes throughout the course of the year. To identify the developmental characteristics, it is important to look at the interviews longitudinally.

Other evidence I will be looking for in the interview data is evidence of expertise in the students, specifically, relationship between energy and other analytic methods, connectedness of their knowledge bases, the development use of representational tools, and existence of models as epistemological anchors and energy as an epistemological resource. Primarily, this evidence would likely be near the end of each semester, but could come from earlier interviews as well.

Longitudinal Analysis of Interview Data

The longitudinal analysis of the focus group interview data will focus on the evolution of the understanding of energy conservation, and the students' notions of energy. Understanding the essence of energy is not in and of itself an important feature, however, it is important to understand energy *is not* a force, to be able to distinguish potential and energy, energy and electricity, and power and energy. A preliminary round of interviews conducted in a previous course, which included a rough version of the energy thread, revealed all of these difficulties. The energy thread curriculum emphasizes energy in a variety of ways that helps establish the distinctions between energy and these other quantities. Furthermore, the energy thread should develop the understanding of energy conservation and the subtleties of energy conservation beyond the superficial understanding demonstrated by students initially.

The initial set of interviews are the most difficult to analyze because the students' understanding of energy concepts is incoherent. One of the consistent features of the initial interviews is the students' ability to recite 'energy can not be created or destroyed.' While one student discussed energy transformations, another was able to distinguish local and global conservation, and a third recognized the importance of system when solving problems with energy conservation, the remaining five students were non-committal about energy conservation. A student from the Year-Long group exemplified this attitude with the following statement, "It's never lost, it's never gained. I think you can create *some kind* of energy, I think I learned once that you can create energy." I asked another member what conservation of energy meant to her; she responded, "I just remembered it was one of the laws, the conservation of energy." Though the students were able to state conservation of energy they had not ascribed any meaning to it.

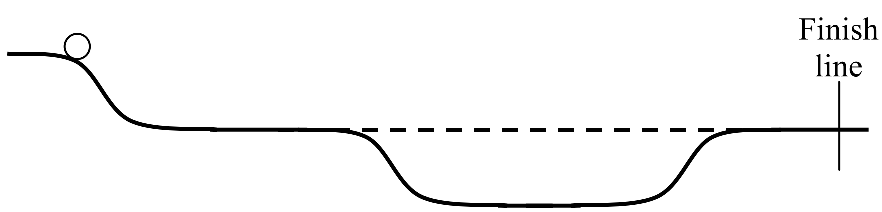
The students' initial understanding of the nature of energy was indicative of an impetus model for energy, which does not support an understanding of the conservation of energy. Only one student gave the expected response, which was "The ability to do work." When I asked this student what work is, he responded, "…whatever that requires energy to set it in motion and keep it going." Even this student that had a standard definition for energy, saw energy as a necessity for motion. Another response described a variant of the impetus model, which was not restricted it to motion, instead this student saw energy as a fuel, "A fire needs energy to burn." The primary response involved energy as an impetus for motion, which was further borne out by the situation that the students analyzed. In their analysis, most students saw friction as an energy sink. The ball stopped rolling when the friction 'took away' the energy from the ball. In the impetus model energy is the ball's 'go power'.

By the second interview, five weeks into the semester, students were beginning to drop the impetus model for energy, though not completely. Four students described it as required for motion. These four, however, were less satisfied with their definitions. One mentioned that he related heat and sound to energy, but that heat and sound did not fit into his description. Another student struggled to justify different forms of energy with the impetus model. Others also described various forms of energy and suggested the forms could be transformed from object to object.

Aside from the descriptions, the shift away from the impetus model could be seen in the analysis of the situation. Again they discussed a ball rolling, and this time, the discussion of friction was not as an energy sink, but as a way to transfer energy to the track or as an energy itself. This distinction must be attributable to the use of energy pie charts and system schema because friction had not been discussed in the interim except as it related to energy pie charts. While students began shifting away from the impetus model, their understanding of energy conservation improved.

When asked if energy was conserved in relation to the physical situation they had addressed, students often referred to the energy pie charts. In this manner, they were able to describe energy transferring or changing form, and point out that it was not being destroyed. Heat and sound became important issues in relation to energy conservation; often students talked about energy being transferred to these quantities.

Energy conservation was not simply an abstract principal; the students also used energy conservation to analyze the physical situation presented at the beginning of the second interview. The situation they analyzed is shown in Figure 16.



The above drawing shows two tracks each with a ball on it. The red (here represented as dotted) ball will roll down the red track (dotted line). The black ball will roll down the black (solid line) track. Which ball will reach the finish line first? The balls are identical in every way except color.

Figure 16. Physical situation presented in Focus Group Interview #2

In this situation the students correctly described the increase in kinetic energy as the black ball rolled down the second hill and the subsequent decrease as it rolled up the other side. However, they did not use the pie charts explicitly and did not consider the time when the black ball was traveling faster than the dotted ball. As a result, they came to the conclusion that the balls would arrive at the finish line at the same time, based on the balls having the same energy at the beginning and the end. This analysis, while incorrect, is the product of a valid problem solving approach.

By the third interview, ten weeks into the first semester, the students have effectively dropped the impetus model for energy and the bulk of them have replaced it with an interaction model. In the interaction model, energy is known to be transferred and conserved and is seen as a way to describe interactions. The primary motivation for the interaction model is the parallel treatment of forces and energy, which had been the emphasis of the class between interview #2 and interview #3. Again, the interview began with an analysis of a physical situation, for interview #3 it was a Modified Atwood's Machine, which can be analyzed either with forces or with energy. Each group began by creating a system schema, and then discussed a solution approach. A member of the Hour Long group advised that both approaches would work, but personal preference was not the only thing that determined which to use, "I think it would matter what you are trying to find, actually. There are some instances where I think energy would be to your advantage…" Others suggested choosing the method that was easier: "We are going to look at each situation, and say, of our different tools, which is the easiest way to solve the problem." The discourse on the solution approach shows that energy is as viable an option to students as forces, and this can also be attributed to the parallel treatment of force and energy.

The practical understanding of energy concepts was consistent with the description of the nature of energy, in which students described an interaction model. The interaction model is fostered by the parallel treatment of force and energy by using each as alternate ways of describing interactions. Students recognized this, stating that energy was related to force through the interactions. The interaction model is more nebulous than the impetus model, but it does not interfere with the understanding of energy conservation and enforces the connections between force and energy approaches. The origin of the interaction model is that either forces or energy can be used to analyze the same interaction.

When the students described the conservation of energy, they all recognized that the system was of critical importance. They agreed that, overall, energy was conserved, and in the situation they had described, the system they had chosen required that energy be conserved. One student expanded on this, saying that, since everything is within the system boundaries, even though friction can cause energy transfers, the transfers can only occur within the system. Therefore, energy is conserved. This is indicative that the students had dropped the impetus model, friction was seen as an energy transfer mechanism, rather than as an energy sink.

Interview #5, which was a summary interview, occurred before the beginning of the second semester. It was different than the other interviews, the students were not given a situation to analyze; the discussion was instead focused on their expectations for the upcoming semester and reflections on the previous semester. In the course of this discussion, only one statement was made relating to the nature and use of energy. A student from the Hour Long Group described energy as the basis for establishing models.

The sixth interview took place five weeks into the second semester and had students from both the Year Long and Hour Long groups further describing the interaction model. Prior to the sixth interview, the concept of electric potential had been covered, and students attempted to modify the interaction model to include potential. They described energy as the result of or description for interactions, but in the case of potential, they decided it could be a possibility for an interaction. This is best described by a student from the Year Long Group,

> …energy is a measure of the interaction between two objects…Now recently, in class we've started talking about potential versus potential energy an the two are directly correlated…it seems like it would be a way to explain energy without having an interaction. If I say energy is an interaction between two objects, it seems potential is energy with only one object.

The interaction model was also evident as they interpreted the potential interaction energy graph presented in the sixth interview. As a major component of the interpretation, they discussed that the graph did not only contain information about energy, but it also included force vs. distance information. The graph was interpretable in either way. They saw a strong relationship between force and energy, noting that for the same interaction either interpretation of was possible.

The interpretation of the potential interaction energy graph provided an interesting perspective on their understanding of energy conservation. In this representation, only the potential energy was shown, but the students were able to infer the kinetic. Both groups discussed that the inferred kinetic energy was dependant on the system defined. They recognized the possibility that there were other interactions, other objects, and hence, only if they made some simplifying assumptions about what constituted the system could they discuss energy conservation. Their understanding of energy conservation, always included the need for a system, and they were able to make inferences about the characteristics of systems where energy would be conserved and where it wouldn't.

By the seventh and eighth interviews, which occurred during the 13^{th} and 15^{th} weeks of the second semester, the discussions of energy conservation were brief. The brevity of the discussion was indicative of the level of understanding. Instead of displaying the need to explicitly discuss the meaning of energy conservation, the groups acknowledged the importance of system, and that energy was globally conserved and moved on. They *did* demonstrate understanding through the use of energy considerations. In the seventh interview, the students used energy conservation to reason about the field creating an equipotential surface, and they were able to correlate the energy interpretation with potential, force and kinematic interpretations of the same modeling tool. In the eighth interview the situation presented to the groups was one that according to the course content, they were not prepared to explain. They were asked to model the following situation, "A block of metal is placed in a very hot oven. It heats up and begins to glow, then it finally melts." They attacked the problem from an energy perspective and were able to incorporate ideas about heating, radiating, change of phase of a metal, thermal expansion, the energy dependence of various colors of light and described the steady state for energy in terms of energy transfers within the system. The students accomplished all of this by exploiting energy conservation principals. Unlike the beginning of the semester, when they were only able to *state* conservation of energy, at the end the year, not only could the students still state it, but they also now demonstrated understanding of many of the subtle nuances of energy conservation.

Students' understanding of the nature of energy also developed during the year. During the seventh interview, a student described it this way: "energy is very complex…I don't really know what energy is, except for I know the way we've used it this year. We've used energy to model interactions between objects." This response is characteristic of the interaction model. A quotation by Richard Feynman provides a pertinent distinction between the students' understanding of energy at the beginning of the year and their understanding at the end of the course.

> You can know the name of a bird in all the languages of the world, but when you're finished, you'll know absolutely nothing whatever about the bird... So let's look at the bird and see what it's doing -- that's what counts. I learned very early the difference between knowing the name of something and knowing something.

The students struggled to define energy during the eighth interview. The following quote demonstrates one students' struggle. "I couldn't find a good definition in the dictionary either. It is circular reasoning…they say energy is the ability to do work, and then you look up work-the ability to have energy." One student responded, "I think most people would define, before, I've learned it is the ability to do work, but I think we described it more in this class." The student, R, who had looked up the definition concluded, R: I think energy is something physicists have used to explain what happens. Like the way they couldn't explain why a positive charge repels another positive charge, so they came up with fields. I think that's what happened with energy. They used it as an explanation, like a model.

P: It's a really good model though.

R: Yeah, yeah, they are smart, they are on the ball.

In looking at the development of the students' understanding of energy (both the conservation and the nature of energy), there is evidence that the energy thread curriculum has been successful. The students developed a deep understanding of energy conservation and in the process, rejected an impetus model for energy, adapting a more sophisticated interaction model for energy. These are characteristics of more expert physicists, energy conservation is no longer, "just one of the laws" as stated by one of the students in the initial interview, but a practically useful approach to analyzing situations.

Summary Interview Analysis

In addition to analyzing the interview data longitudinally, I have compiled evidence that the students were gaining expertise. Specifically, I found evidence of connections within the students' knowledge bases, and evidence that they came to view models as the epistemological anchors and energy as a ubiquitously practical analytic approach.

Connected Knowledge Bases

The greatest evidence of connections in the students' knowledge base was an outcome of the analysis of situations at the beginning of the interviews. Some of the first indications of the connectedness of their knowledge base came with the interaction model of energy. The interaction model resulted from the parallel treatment of energy and forces as equally valid approaches to solving problems. It is no surprise that the first interaction model was proposed in the third interview, which was near the end of the first treatment of forces and energy. In the third interview, the students analyzed a Modified Atwood's Machine. Each of the groups discussed approaching the problem from both a force and an energy perspective, and the Year Long Group went all the way through the solution both ways. This was the first time in the interviews the situation was analyzed from more than one perspective, and it showed that the students were looking at interactions as the coupling between the methods.

In later interviews, the students also analyzed the situations from multiple perspectives. In interview 6, they not only discussed force and energy, but they also related these concepts to field, and potential. They interpreted the interaction energy graph in terms of force, by taking the negative slope of the line. Through the graph, the students were able to create not just conceptual connections, but connections based on interpretation of the modeling tools. During the seventh interview, students inspected a motion map for an electron, from this kinematic representation they argued that there must be a net force caused by a field, and that it also meant that the potential energy must have been changing. One student described the process of creating the connections by investigating what happened to a single charge:

> …we know that's a charge and its mass stays the same, and because it is accelerating, it is going to have a change in velocity. With the tools that we have and the equations that we know, we can start seeing how those little pieces can work for force, and how they can work for field. And how, in that way, it is related to just those small pieces of information. We can obtain all these other important things….At first when we looked at it (the electron) the first thing we said was, 'Well it's probably going to accelerate to this side because of the potentials.' From the acceleration, since the mass is staying the same it is going to have a force, and since there is a change of velocity and it's a charge it's going to have a field. Little things like that, just building on things like that, snowballing into something bigger.

These are interpretations relating one of the first modeling tools introduced to modeling tools related to electric fields and potentials. From these interviews, it is evident that the students have created explicit connections between modeling tools representing different phenomena, as well as conceptual connections related to the interaction model. These connections were not simply within physics, one student reported using the force diagrams to do his engineering homework, another student, student S in the passage below, described thinking back on her high school experience,

> S: For me, in like Bio, Physics, and Chemistry, I learned about it (energy) in each in different forms, like chemical energy, exothermic, endothermic, physics it is

> the ability to do work, and in Bio, it is like ATP molecules formed. That's how I learned it in different things…I think they are different forms of how you store energy. But you use them for the same thing.

Energy as a Ubiquitous Analytic tool

The goal of the energy thread is to induce greater expertise in students. They already see forces as a ubiquitous approach (often to a fault). In the energy thread curriculum the attempt is to emphasize the utility of energy considerations as a ubiquitous analytic approach. This is in line with expert practice in physics. In order to determine the success of this, it is important to investigate the students' views. Luckily, during the seventh interview, one student described how he had proceeded with the analysis of the equipotential surface at the beginning of the interview. He said,

> That's (energy is) kind of the basis of what I was thinking…force is the negative derivative of energy, but aside from that, it seems to me, energy was more of a ubiquitous principal. Forces were too, but forces really were of use when things were accelerating. Whereas, generally, to solve a problem, I don't want to make the solution complex, I'd like to avoid that, so I'd usually use energy to solve for things.

Other students said similar things, the following interaction between "M", "D" and "G" from the seventh interview shows the students thinking not only about energy but also about its relationship to force and how the two, together, constitute a superior approach.

> M: An object can have kinetic energy and not have force.
>
> D: Right, but can it have a change in kinetic energy without a force?
>
> M: No.
>
> D: And energy deals with changes, cause everything is based on a change from A to B. And a force is just an instant of that change. So they seem to be tightly intertwined. To a point where I'm not sure where one ends and begins.
>
> G: I see how you need both of them together, because if you have one without the other, you are not going to be able to get a lot of things out of a certain situation as you would if you have both. Well, like D said, they are really closely intertwined…It's like a pair that are important.

By the end of an entire year, students see energy as indispensable, and of equal value as forces. In the second discussion, they describe the need not just for one or the other, but for both together. This is the goal of the energy thread, to promote energy to a status equal to forces. This way, I can say that the students see energy conservation as an epistemological resource of equal value to Newton's Laws for forces.

Models as Epistemological Anchors

I have described models as the ideal epistemological anchors, because they are the basis for knowledge organization. In the summary interviews, 5 and 8, students spent considerable time reflecting on what they had learned over the course of the semester or year. During these interviews, they revealed what was important in their learning. Students in these interviews revealed that they saw the models as the anchors for their learning. The students apparently began seeing models as the anchors as early as the first semester. In response to the question, "What did you find were some of the most useful things as far as learning physics?" one student responded, "I had previously had physics and it wasn't a problem…But, I never had actually laid out the models…Every model that we have had, we can use, and it has been transferred to math and everything else." In a separate interview, another student described modeling as the most important thing he had learned. "…we learned a lot of ways to make assumptions. Modeling, and little things that help us find answers that aren't really in the textbook."

Aside from identifying models as important to learning physics, students from both groups during the eighth interview described the foundations of the class. Students from the Year Long talked about solving problems and described modeling as the foundation of the class. They characterized it as a critical process involved in solving problems where they first set up the assumptions, then the representations and then finally get answers. One student explained the power of creating a model rather than just solving an equation.

> I think, not only, helping to get the answer, it justifies why that answer is right. You have evidence supporting that answer, rather than some physics class where you are given a problem and just plugged in the numbers for the equation. What

> we have by showing these diagrams, we're showing proof, to back up that numerical answer we get.

These two summary interviews allowed the students to describe their view of the utility of models. Students from both groups identified models or modeling as the most important tool for learning physics. These attitudes are indicative that the students put models at the center of their learning of physics. They used models as the epistemological anchors, which their physics understanding clung to.

Chapter Six

Discussion and Conclusion

The purpose of this dissertation has been the definition and explanation of the energy thread and to explore the effects of including such a coherent conceptual and thematic thread in the introductory physics curriculum. The energy thread exemplifies a restructuring and reorganization of the content of the introductory curriculum. In reorganizing and restructuring, the energy thread curriculum induces in students a number of facets of expert practice in physics. Among the expert characteristics included were improved use of representational tools to guide qualitative analysis of physical situations, greater reliance on problem solving methods other than forces and Newton's Laws, and to use the energy thread to provide long-term organization to students knowledge base by developing it as an epistemological resource.

Energy considerations are not given proper consideration in a force-centered curriculum. There is an extensive set of powerful modeling tools related to energy, which are not commonly utilized in traditional instruction. By including an energy thread through a model-centered curriculum, students are empowered with these tools. Since the quality of the model is constrained by the modeling tools available, it is crucial that these tools be included. With the energy thread curriculum as I have implemented it, students gained expertise at using and interpreting these tools to qualitatively analyze a broad array of situations. These tools are not simply introduced once, instead the tools are continuously reintroduced and reinterpreted in order to give importance to the tools as part of a complete specified model. As a result, students are encouraged to rely on the tools and utilize them in solution of problems.

In a standard force centered curriculum, the different subjects in the class are treated as isolated units. The unit on forces has little to do with the unit on energy, which has little to do with the unit on momentum. This does not promote the rich cognitive connections between the separate units and therefore leaves student knowledge bases fragmented. This fragmentation of the knowledge base is further promoted by encouraging students to solve large numbers of problems and viewing a problem solution simply as a numeric answer and viewing the *problems* as the epistemological anchors for physics. Students in the energy thread curriculum, which is a *model-centered* curriculum, are encouraged to view a rich specified model as the solution to a problem and *models* as the ideal epistemological anchors in the physics curriculum.

A thorough specified model includes coordinated representations of forces, energy, momentum and kinematics as well as other structures. Coordinated representation of these quantities, helps create connections between the quantities, which are intrinsically linked. The energy thread further cements these connections by reorganizing the curriculum to treat the topics in parallel rather than sequentially. This content reorganization aids students in the creation of better organized knowledge bases as well as discouraging force-only problem solving approaches and encourages the use of a wider variety of problem solving approaches.

The energy thread content restructuring and reorganization has been designed with the intention of improving the level of expertise in novice students. In order to address my research question, “How does including a long term conceptually and thematically coherent energy thread effect the level of expertise in novice students?”, I have looked at a wide range of data. Overall, the data supports that by including a carefully designed and implemented energy thread in the introductory curriculum, students attain a greater level of expertise.

A preliminary indicator of the successes of the energy thread curriculum came from RAPT data sharing between North Carolina State University, and Arizona State University. Further data on standard instruments shows, that including the energy thread did not compromise the treatment of forces concepts or concepts of electricity and magnetism. The RAPT data shows that energy thread students gain an understanding of potential beyond that of students *without* the coherent conceptual thread.

Problem solving data shows that students taught in the energy thread are more likely to use energy concepts in solving problems when it is appropriate and gain an intuition about appropriate usage of energy considerations. Furthermore, students employing energy considerations to solve problems are more likely to correctly solve the problem than if they had employed a force approach. This can be linked to the relative simplicity of the scalar quantity energy over the vector quantity force.

The energy thread students also demonstrate an improved use of representational tools to qualitatively analyze problems. Problem solutions evaluated on the problem solving rubric, established for this study, showed significant differences in terms of overall problem score and scores based solely on representation and analysis. Students with higher scores were shown to be more likely to correctly answer the problems. The greater reliance on problem representation to analyze situations led to a greater likelihood of solving the problem.

Problem representation and analysis are key components to creation of a rich specified model. Not only do students in the energy thread curriculum create models to effectively solve problems, but the models have also become the epistemological anchors for their knowledge bases. The interview data illustrates that students found the models as the most important, most central thing they learned over the course of the energy thread class. Models were described as being universal and applicable in physics as well as chemistry, biology, and engineering classes. The process of modeling became synonymous with the process of "doing" physics, or perhaps science in general. Students described the explicit use of assumptions and the challenge of determining the limits of validity of their model as critical components to a physics class, and that these components can not be found in textbooks.

Students valued the process of modeling. Modeling does not favor a force approach, nor does it favor an energy approach, each approach is valued equally. This equal valuation is not apparent in the standard treatment of energy concepts. In the energy thread curriculum, students consider either forces or energy as valid epistemological resources for interpreting models. The students in the interviews described this by explaining the utility of either approach. Students saw energy not as a last resort, but as an approach which is universally appropriate for analyzing and interpreting physical situations.

This study has not shown incontrovertibly the energy thread has enhanced the expertise of novice physics students. A number of factors limit the scope of the conclusions that can be drawn; small sample size, the lack of data from the second semester, weak interrater reliability and the small number of comparison problems all need to be addressed. However, the data that exists all suggests the energy thread contributed to the development of expertise in novice students.

The energy thread curriculum has the potential to enhance the level of expertise among novice physics students. In this implementation of the energy thread, this potential has been realized. Improvements are possible, and extensions of the energy thread abound. In these final sections, I make suggestions to instructors interested in the inclusion of an energy thread curriculum and then finally recommendations for further research.

Recommendations to instructors

"An expert is someone who has made all the mistakes" - H. Bethe

Implementing the energy thread curriculum is not like following a recipe, it has to be adapted to the special conditions and constraints of the specific class being taught. There are general rules which can be helpful either by design or by repeated failure.

- The first and most important rule is, students will adapt to the level of expectations placed on them.
    - Students should not be underestimated, they are capable of impressive levels of reasoning and thought.

    - Introducing models, modeling tools and the energy thread will not work if the students do not see the practicality of these things. They must be incorporated into the classroom discourse, the expectations from the instructor and the assessment.

- As an instructor it is important to be aware of and careful of personal biases. Being accustomed to solve a particular problem in one way, does not mean that is the only way to do it. I am constantly learning from my students, because they are unaware of the tradition of certain problems or approaches.
- Concepts should be treated qualitatively as well as with equations. Useful models involve a number of representations of a situation, including verbal/descriptive.
- Representational tools should be utilized in order to reduce the shock of abstraction. Students are often lost as to how to solve problems because they 'Don't know where to begin.' Transitioning from a problem statement to an equation is a difficult task, which requires a jump from a tangible representation to the most abstract representation. Creating representations can make this leap more like climbing a set of stairs.
- Introduce details as they become pertinent. Including too much detail at the beginning overwhelms students. Simple models are easier to comprehend than complex models and often provide adequate interpretation of a situation.
- Treat forces and energy in parallel, this is the most significant reorganization of the energy thread. The two sets of epistemological resources have equal

validity and are routinely used in parallel. They should be treated as such in the instruction. The energy thread is about creating connections, and nothing has been more effective.

- Introduce topics that are more modern, even if it is out of line with what has traditionally been done. The level of student interest for these topics is high, and it is the responsibility of the instructor to keep the instruction of physics pertinent to the general physics community.

With these recommendations to instructors, I hope to steer them away from the mistakes that have been made in the developmental stages of this curriculum, and guide them toward the successes of the energy thread instructors. Or at the very least make them feel better when they make the mistake for themselves.

Recommendations for Further Research

One of the fascinating things about the energy thread curriculum is its versatility. I envision two primary tracks for further research involving the energy thread. First, due to the mathematical simplicity, the energy thread would be ideally suited to high school or middle school curricula. In fact, because energy is a ubiquitous topic for other sciences as well, the energy thread could spread as far back as elementary science, as a unifying theme. High school physics classes could then avoid the use of vectors, which tends to focus the class not on the physics but on the mathematics.

The second track for further research, which I hope to soon pursue, is a radical reorganization and restructuring of the introductory physics curriculum involving the third semester of physics, which is now typically called Modern Physics. With the freedom afforded by reorganizing three semesters instead of two, the changes can be more drastic and possibly more fruitful. The topics in the Modern Physics course would be ideally suited to the energy thread. Thermodynamics, interactions of light and matter, quantum mechanics and relativity all are ideally suited treatment with the energy thread. A structure of matter theme can be more effectively overlayed with the energy thread, engaging students in 20^{th} century physics. Only at that point can one of the true intentions for the energy thread can be actualized.

Conclusion

By restructuring and reorganizing the curriculum with the characteristics of expert practice as a goal, the energy thread has emerged. While I can say with confidence that the design goals have been met, there is still possibility for improvement. It has been shown that students have benefited from the work thus far, I can only presume, with further improvements, the benefits will be greater.

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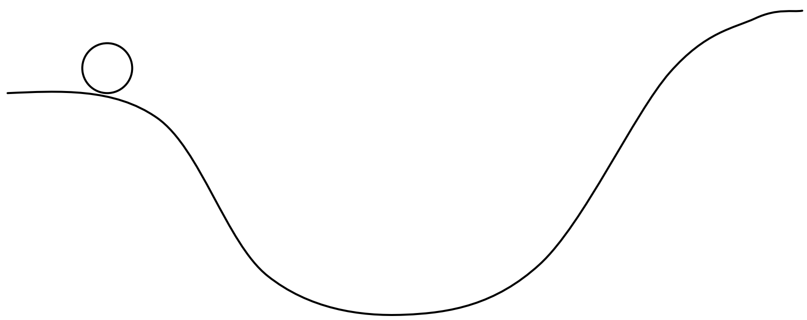
APPENDIX A

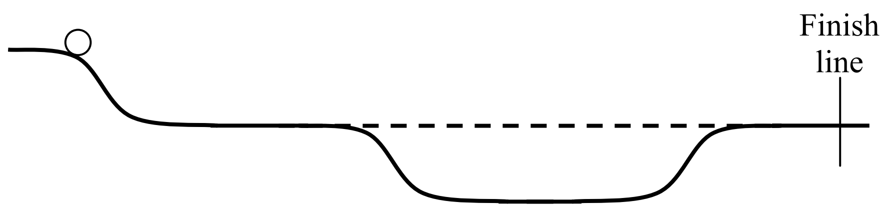
FOCUS GROUP INTERVIEW QUESTIONS

Interview Questions, Interview #1



- What is going to happen to the ball once it is released? Feel free to use the whiteboard and the markers.
- If you wanted to know how fast the ball is going when it gets to the bottom, what would you do?
- Does energy play any role in the description of what happens with the ball in this situation?
- What I would like you to do now, is individually, describe what you think energy is.
- What do you know about energy?
- How do you know when something has energy?
- What does it mean to you when someone says energy can not be created or destroyed?
- What role does energy play in a physics class?
- What role do forces play in a physics class?
- Do you have any questions for me?

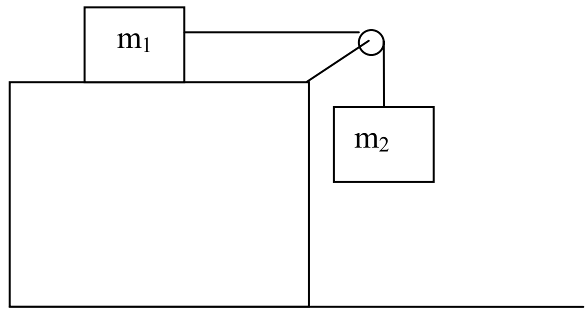
Interview Questions, Interview #2



The above drawing shows two tracks each with a ball on it. The red (here represented as dotted) ball will roll down the red track (dotted line). The black ball will roll down the black (solid line) track. Which ball will reach the finish line first? The balls are identical in every way except color.

- If you wanted to know how fast each ball is moving when it reaches the bottom of the first ramp, what would you do?
- Does energy play any role in this situation?
- Is energy conserved in this situation?
- Individually, I want you to describe what you think energy is.
- Describe how you think energy has been used in the class so far.
- Do you have any questions for me?

Interview Questions, Interview #3



In the drawing above, there are two masses connected by a string, there is friction between mass 1 and the table. How would you go about solving this problem?

- What determined what method you decided to use?
- In this situation is energy conserved?
- Describe what you think energy is.
- Would each of you describe how energy has been used since the last exam?
- Are there any questions you would like to ask me?

Interview Questions, Interview #4

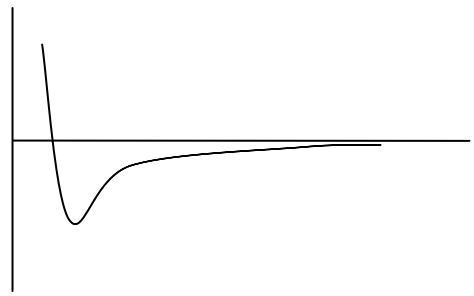
Written on the whiteboard, when the students walked into the interview room were the following situations: After a very hot sunny day a sidewalk cracks. A pot of water boils and evaporates.

- How can you explain the phenomena on the whiteboard?
- Is energy conserved in the situations on the board?
- Describe what you think energy is.
- How has energy been used in the first semester?
- How have forces been used in the first semester?
- Do you have any questions you would like to ask me?

Interview Questions, Interview #5 Second Semester

- Looking back at last semester, what did you learn during the first semester, and what do you expect to learn this semester?
- What among the things you learned during the first semester did you think were useful?
- Were there things you found useless or less useful?
- Do you have any questions for me?

Interview Questions, Interview #6



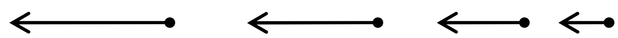
Tell me as much as you can based on the graph drawn on the whiteboard.

- What kinds of things can you use explain based on this graph?
- Does this graph tell you only about energy?
- In this situation, is energy conserved?
- Describe what you think energy is.
- How do you know if something has energy?
- How do you know if energy has changed?
- What do you think the role of energy has been in the second semester thus far?
- What do you think the role of forces has been in the second semester thus far?
- Do you have any questions you want to ask me?

Interview Questions, Interview #7

(The following situation description is written on the whiteboard):

A positive charge, initially at rest, is released and it moves to the left. The motion map shown below describes the motion of the positive charge. Tell me everything you can about this situation.



- How did you begin to analyze this situation?
- Is energy conserved in this situation?
- Describe what you think energy is.
- Do you have any questions for me?

Interview Questions: Interview #8

The following situation is written on the whiteboard when the students enter:

“A block of metal is placed inside a very hot oven, as it heats up it begins to glow and then it finally melts.”

Give a complete physical description and explanation of what happens in this situation.

- Has your physics class prepared you to answer this question?
- Looking back on the entire course, do you feel like the class covered enough material?
- What about this class do you think helped you learn to solve problems?
- What tools did you find the most useful during the course of this year?
- Describe what you think energy is.
- Do you think the way you think about energy has changed over the course of this year?
- Do you have any questions you would like to ask me?

APPENDIX B

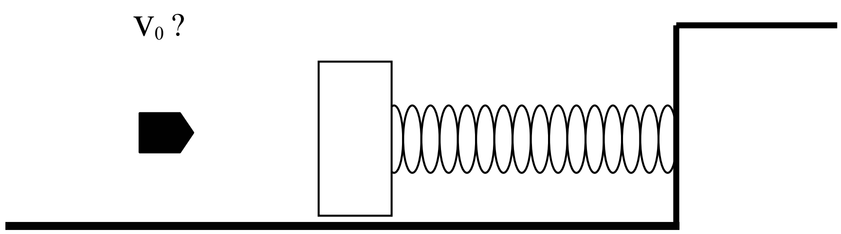
COMMON EXAM PROBLEMS

Question #1 for Mechanics:

A sled of mass *m* is given a kick on a frozen pond. The kick imparts to it an initial speed of $v_i = 2.00$ m/s. The coefficient of kinetic friction between the sled and ice is $\mu_k = 0.100$. Where does the sled stop?

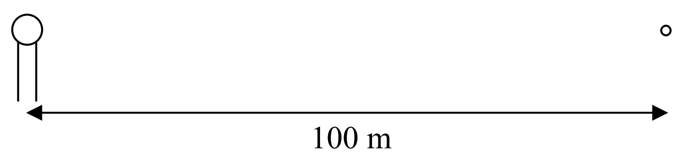
Question #2 for Mechanics:

A 0.10-kg bullet is fired into a 1.90-kg block. The block is attached to a spring of force constant 1000 N/m. The block slides for 0.40 m while compressing the spring after the bullet runs into the block. Determine the bullet's speed before it hit the block. Assume that the gravitational constant is 10 m/s^2. You must show all of the work supporting your answer or no credit will be given.



Question #1 for E&M:

A very small metal sphere is at rest on a stand and is positively charged to $Q = 1.6 \times 10^{-16}$ C. A proton is fired from a distance of 100 m directly at the sphere at a speed of $v_{proton} = 1.0 \times 10^{6}$ m/s. Where does the proton turn around?



Question #2 for E&M:

Two large plates of a particle accelerator are separated by 0.050 m as shown below. The negatively charged plate on the left has a very small hole in the middle of the plate to allow the particles to escape. The magnitude of the electric field between the plates is $E = 100$ N/C, the potential difference between the plates is $V = 5.0$ Volts. A proton ($q_{proton} = 1.6 \times 10^{-19}$ C, $m_{proton} = 1.7 \times 10^{-27}$ kg) is placed at the positively charged plate on the right and released. What is the speed of the proton when it reaches the hole on the left plate?