A NEW HIGH SCHOOL SCIENCE PROGRAM AND ITS EFFECT ON STUDENT ACHIEVEMENT IN MATHEMATICS AND SCIENCE

By

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A dissertation submitted to the
Graduate School of Education – New Brunswick
Rutgers, The State University of New Jersey
in partial fulfillment of the requirements
for the degree of
Doctor of Education
Graduate Program in Education

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October 2006

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DEDICATION

I dedicate this dissertation to my entire family, who has always supported me in whatever interests I chose to pursue. That required sacrifices as I moved from a lucrative business career to the teaching profession: they never complained. In fact, I received encouragement from them every step of the way. That was true of my parents, Marge and Walter; my wife Nancy; by brother and sister, Larry and Carol; and my children; Andrew and Katy. What a wonderful group of people.

ACKNOWLEDGEMENTS

My work would not have been possible without the support and encouragement of both the high school in which I teach and the school district of which it is a part. It is unusual for schools to allow teachers to try new ideas and build on them from year to year. Dr. John Grieco was an exceptional educator in that he built a school district on that philosophy; my work over the last seven years was a result. It is unfortunate that his untimely death did not allow him to see this particular result of his efforts.

His successor, Robert J. Aloia; the district's Board of Education; and the district's Central Administration also deserve thanks for their encouragement for me to continue building my school's program for science and mathematics; to document that program; and to evaluate its results. Without their support this dissertation would not have been possible.

I was fortunate to have worked with two talented and open minded school principals who lent me inordinate amounts of support and encouragement. My first principal, Sal Mastroeni started me on this work. He was succeeded by Andrea Sheridan, who ranks as one of the finest people with whom I have worked. I also received a great deal of help from a number of the school's administrators, including Linda Bernstein; Patricia Carroll; Michael Polizzi; Karen Steele; and Ted Szczawinski; the secretarial staff headed by Marion Callahan; and the school's exemplary custodial personnel led by Dave Bonardi.

I'd like to thank the more than twenty science and mathematics teachers who played important roles in implementing the program described in this dissertation. Each of them deserves to be thanked for their efforts. However, I'd especially like to thank my fellow physics teacher, Yuriy Zavorotniy, and the chair of our mathematics department, Larry Gilligan. They well represent the excellent science and mathematics teachers in both departments.

I chose to do my graduate work at the Rutgers Graduate School of Education in order to work with my dissertation advisor, Eugenia Etkina. I have never regretted that decision. Eugenia is a passionate uncompromising educator who is bent on improving American science education. Our many heated arguments about science education have helped shape my perspective.

I was very fortunate in having such a talented and committed dissertation committee. I had previously taken courses from Richard Duschl and Clark Chinn and both of them were instrumental in developing the theoretical understanding that supports this study. I was fortunate that they were willing to continue working with me through the writing of this dissertation. While I had never taken a course with Warren Crown, his perspectives from the discipline of mathematics were critical to this study, particularly because this was a study of a program whose goals were in the realm of both mathematics and science.

I also appreciated the support of many of my fellow graduate students, especially David Rosengrant; Jim Neufell; and Trudy Atkins, who introduced me to cladistics, an idea that proved surprisingly important to my theoretical framework.

I would also like to thank Michelle Johnson of Pearson Education for her prompt response to my request for permission to reproduce pages from two of their textbooks.

ABSTRACT OF THE DISSERTATION

A New High School Science Program and its Effect on Student Achievement in Mathematics and Science

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The author led the creation and ongoing implementation of a program designed to improve student achievement in mathematics and science at a New Jersey vocational/technical high school. This initiative began 6 ½ years ago, coincident with the founding of the school, and should be completed in about 2 ½ more years.

My first aim in conducting this study was to determine the effectiveness of the program. Since this was a long term program created in a real world environment it would prove exceedingly difficult to use experimental or quasi-experimental analysis: there were simply too many potential biases and sources of error. However, I was able to develop a plausible argument for the effectiveness of the program by using two measures to create a baseline for student aptitude and three measures to determine student achievement.

Together these analyses showed that the school's students, while typical of those in New Jersey, achieved exceptional results in mathematics and science. The likelihood that the new program was responsible for these results was enhanced by the fact that the verbal and mathematical aptitudes of the

students were comparable to one another but their achievement, in areas outside of mathematics and science, areas that should not have been directly affected by the program, were not exceptional.

Having provided results that were consistent with the conjecture that the program was effective, my second aim was to document the program so that it could be replicated at other schools. I provided a number of documents to support this goal: the scope and sequence of the mathematics and science courses; the curricula for the two physics courses; an explanation of the pedagogical approach that is used in the physics courses; and sample chapters of a physics textbook that a colleague and I are writing to support the first year physics course.

While these documents supply a snapshot of the current state of the program; they are probably insufficient to replicate it; this would also require an understanding for of the program's rationale. Towards this end, I have explained the theoretical framework for the program in depth.

Schools throughout the United States have been charged with increasing student achievement in mathematics and science. This study documents a program that may well be achieving these goals; it could provide an answer for them.

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Statement of the Problem

Student achievement in mathematics and science is a high educational priority worldwide. In the United States, the government has made improved student achievement in these subjects a national objective. This has recently been evidenced by the president's comments in the State of the Union address and the proposed language of the 2007 Reauthorization Bill for the No Child Left Behind legislation.

The American educational system is not meeting its objectives for these subjects; our students are performing below international standards. The problem is endemic, leading to the conclusion that it is structural in nature. As such, its solution will require addressing the very structure of our system of science and mathematics education.

For the last 6 ½ years I have led an initiative to institute a new science program in a vocational/technical school in New Jersey. I am employed by the school in several roles: physics teacher; Pre-Engineering Program Manager; and the lead teacher for science. The goal of this program is to improve student achievement in both science and mathematics and evidence that improvement through student performance on Advanced Placement (AP) examinations. Full implementation of this new program will be complete in about 2 ½ years; about nine years after it began.

In this new scope and sequence; we teach physics in ninth grade instead of biology; we teach biology in eleventh grade instead of physics; and chemistry has remained the tenth grade science. These changes required significant curriculum revisions within the courses: course sequence strongly affects course content. One of the subjects whose curriculum underwent significant change is physics. Also, while these changes are in the sciences; one of the key goals of this approach was to improve student learning in mathematics.

My overall objective in conducting this study was to determine the likelihood that this new program has been effective in improving student achievement in mathematics and science and to document the program so that it could be implemented in other schools. This documentation was crucial; if the program is well documented then it would not take other schools nine years to implement; learning from our experience could cut that time considerably.

This dissertation consists of five chapters, the first being this introduction. The second chapter begins with a review of the literature related to prior experiments with reordered science sequences and then proceeds to the theoretical framework for the current effort. In 1995, Leon Lederman brought a great deal of attention to the concept of what was to become known as Physics First. However, experiments with this idea stretch back to the 1960’s and rich studies of those efforts were available in the 1970’s and 1980’s. That work laid the foundation for the current Physics First movement so it is explored along with the more recent studies.

The second chapter goes on to review the literature that establishes the theoretical framework for the program under study. Since this program involves the real world implementation of a scope and sequence and pedagogy for many interrelated courses taught over a number of years; its theoretical framework involves a large number of interwoven ideas. As a result, the review of the literature that supports the program and this study is necessarily broad. Literature related to perception; cognition; mediational tools; constructivism; mathematics; physics; problem-solving; and transfer are both described and related to one another in order to use their connections to establish the theoretical framework.

The methodology of the study is discussed in the third chapter. This study involved documenting and analyzing the results from a program that has been operating in a school for more than six years and has involved hundreds of students; dozens of teachers; and numerous administrators. It clearly cannot be thought of a either experimental or quasi-experimental in nature: there are numerous biases and sources of error that could be minimized, but not removed, in a school environment over such an extended length of time. Some of these include: selection bias; lack of randomization; lack of a control group; changing experimental conditions; variances in teacher ability; etc.

However, while that made it difficult to statistically analyze the results of the program; it did not lessen the importance of analyzing those results. The third chapter describes a methodology that allows us to draw some reasonable conclusions from the school's experience. It does so by first using SAT results to establish two findings for the students in the school: their aptitude in mathematics and in English are not a typical of students statewide and their aptitudes in mathematics and in English are similar to one another.

Since the program under study was not expected to have had a meaningful impact on English or social studies performance, and the students in the school are close to the average for New Jersey students in terms of both their mathematics and verbal aptitudes, this allowed me to establish two separate but related baselines for comparison: state achievement in mathematics and science and school achievement in English and social studies. Achievement was determined from results on AP exams and High School Proficiency Assessments (HSPA's), the required New Jersey 11th grade test.

AP exams represent one of the few measures of student achievement that is accepted by a majority of high schools, colleges and universities. They are also the closest the United States has to a national high school curriculum and assessment. As a result, they are a valuable tool for comparing student performance between schools and between departments within schools. Increasingly, the participation of students on those exams is also an explicit national educational priority because they represent a program of rigorous study.

The HSPA is given to all students in New Jersey in 11th grade. It provides a comparative measure of performance between schools and between the English and math programs within a school. Since it is given in both math and English; the achievement in both those subjects can be compared to state norms and analyzed.

In addition to the above comparisons, I used participation rates in science electives as a measure of the value student's place on the study of science: an effective science program should result in an increase in its apparent value to students. To the extent that students choose to take courses that are above and beyond what is required of them; that reflects either their interest in the material or their belief that it is important. While participation rates alone cannot determine which of these two factors is motivating students; it does measure their combined effect; an effect which can be thought of as the value students place on the study of science.

The fourth chapter provides the results of that analysis from a number of perspectives. The data show that the students in this school performed well above the state average in the areas of science and mathematics. It is also clear that similar gains were not experienced in the areas of English or social studies. This supports the idea that the program under study had a positive effect on student achievement in mathematics and science; if the effect was due to some more general feature of the school or to selection bias, there should have been similar gains in all subjects. While it is not possible to use the results to prove a causal connection between the program and the gains in student achievement in mathematics and science; a plausible argument is presented. The various data are both consistent with that conclusion and consistent with each other. However, alternative explanations are possible for each of the results and those explanations are also provided. While the results are consistent with the program being effective, each piece of evidence that supports that conclusion could also be explained by some other cause.

The fourth chapter also provides the documentation of the program. The documentation describes and analyzes the science scope and sequence and the articulations created between science courses and between science and math courses; the curriculum and pedagogy of the keystone 9th grade algebra-based physics course and the subsequent 10th grade AP Physics course; and the textbook that is being written to support the 9th grade physics course and captures the manner in which it is taught. Great attention has been given the 9th grade physics course as it is critical to the program: it supports the science sequence and is a principal driver of the anticipated improvement in mathematics achievement. It is also the first new course that any school implementing this program would need to launch and the course whose curriculum and pedagogy are least conventional.

The final chapter discusses the implications of the results in terms of educational policy and in terms of future studies. It is suggested that other schools begin implementing similar programs given the plausible argument that this will result in gains in student in achievement in both mathematics and science: gains in both of these areas represent national priorities. The case is sufficiently strong that there is every reason to proceed immediately.

At the same time, further research is recommended both with respect to the program at the current school, as well as at schools that might adopt the program in the future. Much of that research would focus on the alternative explanations that were given in Chapter 4 for each piece of evidence that supports the hypothesis that the program is effective. The suggested qualitative and quantitative studies would serve to either support or fail to support the hypothesis that this program is effective. Alternatively, that research would serve to support or fail to support the hypothesis provided by the alternative explanation.

Research Questions

Research Questions	Data Sources	Method of Data Analysis
1) What is the new science scope and sequence and how is it unique?	Scope and Sequence	Documentation and commentary
2) What are the new physics curricula and how are they unique?	Curricula for Physics Honors and AP Physics B Courses	Documentation and commentary
3) What is algebra-based 9th grade physics and how is it taught ?	Sample chapter from new textbooks and from two standard textbooks	Documentation and commentary
4) How does the AP perfomance of the students in this program compare to that of students in other New Jersey schools?	School data on the school's AP results	AP participation rates, average scores and AP Metric results
	Public data on New Jersey's AP results	Evaluation of trends by subject area for the school and state
5) How does the HSPA math perfomance of the students in this program compare to that of students in other New Jersey schools and to their English HSPA performance?	School data on the school's HSPA results	The AP Metric that was described above
	Public data on New Jersey's HSPA results	Evaluation of the trends in the AP Metric by subject area
6) What are the trends in the participation rate in science electives?	School data on course and school enrollment.	Documentation and commentary

Table 1: Research Questions

CHAPTER 2: LITERATURE REVIEW

The Importance of Physics and Mathematics

The U.S. is joining other nations in making math and science educational priorities, side by side with language arts. “Mathematics plays a prominent part in the curriculum of every country, usually second in importance only to the mother tongue” (1992, p. 79). In the United States, the first high school assessment requirements, established by the federal “No Child Left Behind Act,” are in language arts and mathematics. Each state is required to assess progress in these subjects by 2004/2005. The next requirement is to assess science by the 2007/2008 academic year.

A reform of the science curriculum is underway in many school districts nationwide. Rather than the traditional order of biology–chemistry–physics, these districts are teaching physics in the first year and biology in the third year. “The rationale for this change is the change the three sciences have undergone over the last hundred years. Biology and chemistry are no longer the purely descriptive sciences they once were” (Pasero, 2003, p. 7). As this change gathers momentum, it is being instituted in high schools nationally. A detailed history of this movement is given later in this literature review.

The original thrust of this approach was to improve the teaching and learning of science. The relative mathematical sophistication required for ninth-graders to succeed in a physics course, as compared to a biology course, was considered a negative feature of this change, not an opportunity. However, some educators believe a major benefit of this new science sequence will be seen in mathematics achievement. "Seen from this approach, Lederman's "Physics First" reform thrust could be *an important opening battle in a full scale war on science/math illiteracy* as envisaged by "Project 2061" of the American Association for the Advance of Science (AAAS 2002)" (Hake, 2002, p. 2).

Whether this becomes the case may be determined by the manner in which ninth-grade physics is taught. At the outset, many conceived of freshman physics as requiring a "conceptual" approach. This was to address the concern that few students understand trigonometry by the ninth grade and traditional first year physics classes require trigonometry. The lack of trigonometry knowledge was to be addressed by minimizing the mathematics in the physics class.

An alternative approach is to teach physics using a mathematically rigorous curriculum confined to algebra. Since most students study algebra by ninth grade, teaching physics built on algebra concepts presents an opportunity to improve understanding in both subjects.

The importance of the mathematics mastered in such a parallel set of courses should not be underestimated. Algebra represents the foundation of much of the mathematics that follows. Students who understand the meaning of, and how to use, algebraic expressions as tools are well on their way to becoming successful in mathematics. Kieran described this as the important transition from procedural to structural mathematics: "Procedural refers to arithmetic operations carried out on numbers to yield numbers…. Structural, on the other hand, refers to a different set of operations that are carried out, not on numbers, but on algebraic expressions" (Kieran, 1992, p. 392). Hiebert and Lefevre described this as the building of conceptual knowledge that weaves together strands of procedural knowledge: “We propose that procedures that are learned with meaning are procedures that are linked to conceptual knowledge” (Hiebert & Lefevre, 1986, p. 8).

Science and mathematics education are compelling national priorities: their importance lie at the foundation of this study. An educational program that advances achievement in both these areas would be of great interest to the educational community. The program analyzed in this study attempts to accomplish that goal, in part, by reversing the sequence in which the sciences are taught. This is not a new idea, but it is an idea whose benefits with respect to science are now being embraced and whose apparent challenges with respect to mathematics are now being seen as potential benefits to mathematics as well.

The Evolution of Physics First

The idea of reversing the science sequence from biology-chemistry-physics to physics-chemistry-biology has been with us for some time. While it became a prominent topic in the 1990’s there were numerous articles written and experiments conducted starting in the 1970’s. Despite that, there have been very few quantitative studies done for a number of reasons: the experimental use of the new curricula has mostly been done at a school level and schools’ limited resources have been devoted to implementation not study; the idea of an experimental or even a quasi-experimental approach with randomly selected participants would have been difficult to justify to students and parents; the curricula evolved over time making it difficult to make clear comparisons.

Despite that, there have been a number of articles and documented cases that are well worth reviewing.

Hamilton (1970) reported on a summer program that was run at Western Illinois State University that involved teaching students that were going on to 10th grade the following year. Eighteen high school physics teachers were involved and a key result was that "the sophomore student had little difficulty in mastering the concepts presented" (Hamilton, 1970, p. 458). The only problem that was reported involved the students' lack of knowledge with regard to trigonometry. "As one teacher put it, 'My students knew the physics of the problem in a few minutes, and then I proceeded to waste an hour trying to get him to express his knowledge in my language, that of sines, cosines and tangents'" (Hamilton, 1970, p. 458).

The topics covered included measurement, force, motion, heat, magnetism, electricity and atomic physics. No reasons were given why these topics could not have been addressed without the use of trigonometry, which was beyond the ability of some number of the students. At the end of the summer, only 25% of the teachers answered in the affirmative to the question, "Should all high school students take physics?" Hamilton did not offer an explanation why the response to this question was so negative; indicating instead that that would require further investigation.

Palombi (1971) reported on an experiment conducted, beginning in 1965, at the Rome Free Academy. It involved teaching physics to some of their 10th grade students; followed by chemistry and then biology. After the 10th grade physics course, the students were mixed with the general population, in other grades, for their subsequent chemistry and biology courses. The results achieved by these students were then compared in all three of their science courses.

Both in terms of their Regents results, this being a New York school, and their anecdotal comments, this sequence produced very positive results. Students uniformly recommended that the school adopt this new sequence and, as a group, they performed better than the average of the school. This showed, "Biology needs chemistry and physics, but chemistry and physics do not necessarily need biology" (Palombi, 1971, p. 40).

Sousanis (1971) reported on the effect of moving physics to tenth grade in a private girls' school, Kingswood, in which he was a physics teacher and the department head. The author did not indicate the science that the students took in 9th grade but did indicate that upon completing 9th grade science, the new sequence became physics in 10th grade; chemistry in 11th grade; and biochemistry in 12th grade. Students were only required to take one science after 9th grade, but the author reported that participation rates in all the sciences became quite robust; 85% taking physics; 70% taking chemistry; and 45% taking the fourth year course, biochemistry. In the five years following the change, which was instituted in 1965, science had moved from being perceived as the weakest to one of the strongest departments in the school.

Sousanis felt that was especially gratifying "given the impediments our culture attaches to a girl's interest in science" (1971, p. 92). He noted that some more advanced students were beginning to take physics in 9th grade and one girl studied advanced physics, using Beyser's *Modern Physics*, and went on to major in physics in college. A number of the girls went on to major in various sciences in college.

Haber-Schaim (1984) made two strong arguments for a physics-chemistry-biology sequence. The first argument involved detailing the prerequisite knowledge for each course based on an analysis of textbooks. He considered a topic to be prerequisite to the textbook if it was relied upon in the book, but not developed within it. His analysis clearly showed that understanding a chemistry text required significant prerequisite knowledge of physics. Similarly, he showed that understanding biology relied upon a number of prerequisite topics from chemistry. There was little indication of required prerequisite knowledge in the opposite direction; chemistry for physics or biology for chemistry.

Haber-Schaim's second argument involved the question of the level of mathematics needed to study physics versus chemistry. He showed that in most cases, the level of mathematics required is the same; with the exception of trigonometry, which is used in physics but not chemistry. But he pointed out that "the use of trigonometric functions is convenient but by not means essential to an elementary treatment of these [physics] subjects" (Haber-Schaim, 1984, p. 332). He argued that the amount of mathematics needed for a first year physics course is provided by Algebra I. The combination of his two arguments led Haber-

Schaim to the conclusion that the proper sequence for science is physics–chemistry–biology.

Myers (1987) laid out the history of the current science sequence in detail and explained how we arrived at the current sequence of biology-chemistry-physics.

> The selection [of sequence] was, at that time [1892], clear cut: 1) Biology in the 10th grade because it relied mostly on memorization and required almost no mathematics. 2) Chemistry in the 11th grade because it relied heavily on memory and meticulous experimental procedures and required modest amounts of mathematics. 3) Physics in the 12th grade because it demanded higher mathematical dexterity and relied heavily on analysis, problem solving and critical thinking. (Myers, 1987, p. 79)

However, science had changed a lot since 1892. Myers used the analysis of Haber-Schaim, described above, to begin making his case for the physics-chemistry-biology sequence; calling the first advantage “Logical Flow”. He then built upon that with a second advantage: “Mathematical Reinforcement”. “In most high schools algebra I is taught to the majority of students during their 9th grade year….Unfortunately they are not called upon outside of mathematics class to use many of these skills until their senior year” (Myers, 1987, p. 79). He pointed out that a physics course taught at, or soon after Algebra I would “reinforce students’ mathematical skills through regular use” and “demonstrate some practical applications and uses of algebra” (Myers, 1987, p. 79).

Myers titled the third advantage for the new sequence: Population Awareness. He defined this as the growing need of the population to understand technology due to the rapid "physics and technological advances that have pervaded our lives – from television to space travel to personal computers to nuclear power plants" (Myers, 1987, p. 80). The new sequence would lead to all Americans having some basic understanding of physics; something that was not the case when physics was being taken as the third, and for the most part optional, science.

Myers also described the results of implementing this new sequence at Choate Rosemary Hall, in Connecticut. He found that participation and interest in science rose rapidly with the new sequence. Also, students were increasingly choosing to take physics first (it was optional to do so); with the result that total physics enrollments steadily increased from 166 to 238, out of a class size of about 250 students, in six years. Enrollment in all the sciences increased and students taking the physics course first performed well above the national average on the NSTA/AAPT national physics test.

Hickman reported great success with students studying physics in 9th grade as compared to students taking the same course in 11th grade (1990). This course was taught in New York, so each student took the Physics Regents exam at its conclusion. He noted that these 9th graders, the first to take physics in 9th grade in his school, outperformed the 11th graders on that examination. He attributed this to the fact that "the algebra that they need most is still fresh in their minds" (Hickman, 1990, p. 47). He also noted that "math teachers find increased interest since the students are *using* the math concepts everyday" [emphasis added]. This idea of usefulness as a motivating factor to student achievement will prove central to this study.

Lederman (1995) focused on the problem that too few a number of Americans, about 25%, attempted a high school physics course. He saw this as a serious problem in that "physics loses a precious number of potentially gifted recruits; the rest of science lose the advantage of students with a solid background in physics; and society loses citizens who have grounding in the kind of critical thinking skills that a good physics course can generate" (Lederman, 1995, p. 11). He agreed with the previous authors regarding the new sequence being more logical but did not seem as comfortable with the idea that most physics problems can be solved with only the use of algebra; a type of mathematics available to most 9th graders; or he felt that algebra and physics cannot be learned in parallel. As a result, he introduced the idea of teaching a "conceptual physics" in 9th grade.

Lederman described a number of textbooks that used this sort of conceptual approach at the same time as he recognized that teaching physics this way "isn't easy. In conveying real understanding, the teacher can't hide behind problem solving" (Lederman, 1995, p. 13). Thus, he attempted to turn the perception that 9th grade students cannot do algebra into a benefit. However, it is unclear how he came to either of these conclusions. He did not seem to have been aware of the successful work cited above where it was shown how 9th

grade students can successfully learn an algebra-based physics to the benefit of their science and their mathematics achievement.

Lederman also discussed the idea of convening “a small workshop of teachers and scientists to produce an outline of a three-year curriculum in which the first year, science I, is largely physics, the second year, science II, is largely chemistry, and the third year, science III, is largely biology” (1995, p. 13). He did recognize that both of these approaches, creating a new sequence based on “conceptual physics” or this new set of three science courses, would involve the massive retraining of teachers. However, this seemed a reasonable price to him, since he saw the need to introduce the sciences in the new order and was not comfortable with solving physics problems based on the algebra that could be expected of 9^{th} grade students.

In a later article, Lederman (1996) built on his previous article in stressing the importance of scientific literacy and the need to revamp high school science education. Once again, he opted for beginning with a “ninth grade course that would focus largely on physics, taught conceptually using familiar language and deemphasizing mathematics so students can focus on the central concepts of motion, energy, heat, electricity, light and the nature of the atom” (Lederman, 1996, p. 62). He recognized that in implementing his approach, “the physics teacher will need to know more about biology and chemistry, and curriculum planners will require a greater degree of collegiality among all science teachers” (Lederman, 1996, p. 63). The likelihood of those two outcomes occurring is not discussed. Nor is the price of separating physics from mathematics; a heavy price considering that that combination is what launched modern science, and some would say, the modern world.

Bardeen & Lederman (1998)extended Lederman's initial idea by introducing the idea that mathematics can be integrated into the 9th grade physics course to advantage. "Science I has a focus on physics, taught conceptually but with enough mathematics to use the algebra learned in eighth and ninth grades. The use of algebra in practical problems not only advances mastery but should spark a realization that 'Hey, this stuff is useful'" (Bardeen & Lederman, 1998, p. 178)! This now sounded more like the algebra-based physics courses that were experimented with successfully in the 1970's and 1980's and less like the "conceptual" course first discussed by Lederman. While the word "conceptual" was retained, it no longer meant "non-mathematical" or implied that "problem solving" was to be avoided. In fact, all physics courses that use mathematics are also conceptual, so the term seems vestigial in this context.

In this article, Bardeen & Lederman (1998) cited the textbook study, described above, by Haber-Schaim to support the science sequence. They added the idea of embedding overarching ideas about science, its nature and purpose, into the three core courses, Sciences I, II and III.

One example of a successful implementation of the new science sequence was reported to have taken place in North Hunterdon High School in Annandale, NJ (Lewin, 1999), where in 1990-91, only 38 students took an AP science course. "The new curriculum brought steady increases in these numbers, and this year [1998-98], a record 226 students are in Advanced

Placement science: 98 in biology, 49 in physics, 41 in environmental science and 38 in chemistry" (Lewin, 1999). The school attributed the gains to the more logical flow of the science sequence.

Robert Tinker (2000) accepted that the new sequence is more logical but was uncomfortable with the change because he felt that traditional physics involved only mechanics. For chemistry and biology to benefit from physics being taught first, he felt that a new physics curriculum would be necessary. His idea involved the teaching of quantum physics as the key to first year physics. He is alone in that opinion and did not seem to recognize that concepts like force, energy, electricity and the basic model of the atom would all represent major benefits to chemistry. It is not clear how the basis of quantum physics could be established without any prior foundation in physics. Or even, how much would be lost if all that students learned about physics was quantum physics.

By 2001, Lederman had made the transition to recognizing that mathematics must be an integral part of this new approach to science. He pointed out that "mathematics must be brought into the curriculum revolution early because math phobia is a near fatal disease unless the student is inoculated at a young age" (Lederman, 2001, p. 11). The importance of wedding mathematics and physics was also indicated by his statements regarding coordinating their curricula. "The math and science teachers must work together in collegial professional development so that the connections of the disciplines are emphasized and the coherent elements emerge. Imagine if the math and physics teacher can design a strategy of the weeks so that Monday's math is used in Tuesday's physics" (Lederman, 2001, p. 12)!

This also led Lederman to conclude that the conceptually based physics books were inadequate to the task: teaching physics in a way that prepares students for chemistry and biology. "They [9th grade physics teachers] use books like Paul Hewitt's *Conceptual Physics* or Arthur Eisenkraft's *Active Physics* which are great books but not designed as a prerequisite for chemistry or biology. So the teachers add, embellish, and improvise" (Lederman, 2001, p. 12). He also indicated that more than 100 schools had switched to the new sequence with consistently positive results; there were no reports of schools switching back.

In 2001, Project ARISE (American Renaissance in Science Education) issued a report on the status of the Physics First movement in the United States (Pasero, 2003). "Project ARISE was born from a workshop held in September, 1995….with the goal to develop a three-year curriculum for high school science" (Pasero, 2003, p. 7). The organization was very much a result of Lederman's impetus and he continues as its leading spokesman.

It was reported that 58 schools responded to survey questions regarding their Physics First programs. Thirteen schools were chosen at random for more in depth interviews. Some common themes emerged. First, mathematics was a common area of concern. While most teachers had wanted to minimize the mathematics in the first year physics course, they found that very difficult. The solutions that emerged all involved integrating algebra into the physics course either by having students take algebra in 8th grade or in parallel with the 9th grade physics course. The solution of teaching algebra to some students in 8th grade and only having those students take physics in 9th grade was undertaken by some schools but was problematic in that parents complained if their child could not take the 9th grade physics course; tracking became a negative consequence.

In general, teachers in the schools were very satisfied; with both biology and chemistry teachers indicating that they were able to make use of prior learning to advance their courses. Students' attitudes were also very positive. There was a need to find teachers who were comfortable teaching 9th graders and knew physics; but this did not seem an overwhelming problem. And, of course, there were reported problems related to the transition period; the need for too many physics teachers during those years when biology was not taught at all and physics was taught in 9th and 11th grade. This argues for a phased, rather than a whole school, transition. Other problems included the placement of transfer students and the lack of a range of textbook options; however, teachers reported that they were happy with whatever book that they were using. The need for quantitative research data was pointed out in this report.

> This may be the most significant finding of this study: Physics-first schools are not quantitatively documenting the degree of their success. Information such as standardized test scores…, enrollment in advanced science courses in high school, numbers of students going on to major in science in college, or any other relevant date would be invaluable. (Pasero, 2003, p. 13)

In April, 2002 the American Association of Physics Teachers formally announced their endorsement of teaching physics as the first of the three core sciences indicating that: “This approach – which we call ‘Physics First’ – has the potential to advance more substantially the AAPT’s goal of Physics for All, as well as lay the foundation for more advanced high school courses in chemistry, biology or physics” (AAPT, 2002). They indicated the need for the following in order for this strategy to be effective: Consultation between teachers and administrators; development of materials and pedagogy; discussion with parents and others; teacher training; and the development of a curriculum for the 9th grade physics course. That curriculum must “provide students an intellectual foundation for the study of chemistry and biology later in their high school education” (AAPT, 2002); tying back to Lederman’s indication that a purely conceptual, non-mathematical, approach for 9th grade physics would not be adequate.

In that same year, Sheppard (2002) pointed out that the history of “physics first” actually goes back to the original Committee of Ten. The section of the committee responsible for science had recommended the current order due to the need for mathematical sophistication to study physics. However, the overall committee “took a contrary point of view and recommended that physics precede chemistry in the curriculum saying that ‘the order recommended for the study of Chemistry and Physics is plainly not the logical one’ (NEA, 1893)” (Sheppard, 2002). Despite this dissent, the order was left as the science sub-committee had recommended and remains the standard order to this day.

Sheppard was the first to add the very critical element of time to the discussion of science curriculum. He points out that one year is simply insufficient to master any of the three sciences. He argued that the current sequence of science is analogous to teaching students Spanish in 9th grade, French in 10th grade and Latin in 11th grade. There is simply not enough time in one year to master any of them: And to then expect a student to take the Advanced Placement examination in Spanish at the end of that sequence, since it is considered the easiest of the three, faces the difficulty that it is also been several years since they have studied Spanish. But this is exactly what happens to most students in science; they take biology in 9th grade and AP Biology in 12th grade. While Sheppard does not recommend how to accomplish it; he made a strong case for spending more than one year studying each of the three sciences.

> Results from the Third International Mathematics and Science Study (TIMSS) put the situation in perspective (NCES, 1998): In physics, U.S. students scored among the lowest of all participating countries….The most important factor determining how well students did in TIMSS was whether students had actually covered the material that was being tested. All the countries that scored higher than the United States had more students taking more physics over longer periods of time. (Sheppard, 2002)

While the American Association of Physics Teacher supported Physics First, Pascopella pointed out that “the American Institute of Physics doesn’t take a position. In fact, Michael Neuschatz, AIP's senior research associate, says many teachers oppose the change" (Pascopella, 2003, p. 2). This was mostly attributed to a lack of trained teachers and money.

Pascopella also pointed out that Rosemary Choate Hall has continued with teaching physics as the first in the sequence and that 145 of 150 entering 9th graders took physics. The head of the science department head, Kathleen Wallace, reported great satisfaction with the program and indicated that students enrolled in Algebra I in 9th grade take Physics while those who had already completed Algebra I take Physics Honors.

Pascopella quoted Lederman as indicating that mathematics was not important to teaching physics in 9th grade. However, she did not give the date that Lederman stated that and as was seen above, Lederman's position has moved towards a more mathematical position over time. She also quoted Jim Jarvis, a physics teacher, disputing that opinion; "without the math, the concepts just aren't there" (Pascopella, 2003, p. 4).

Some 9th graders at "Maryland's Paint Branch High School…are learning math-based physics. Out of about 400 freshman, 88 take the course and have already taken Algebra I" (Pascopella, 2003, p. 4). The school's principal indicated that it is for "the best and the brightest" freshmen. The teacher of that course, David Zaleski, reported that student achievement was as great as it was for students in higher grades and that "you could go a long way in any introductory physics course using algebra skills" (Pascopella, 2003, p. 4). This approach also makes it possible for these students to "take AP biology, AP chemistry or AP Physics in later grades….I see kids in the hallway and they say, 'Mr. Zaleski, we can't wait to take AP Physics next year" (Pascopella, 2003, p. 6). However, no indication was made as to what the other 312 students study in 9th grade and how that tracking affects those students' outcomes in science achievement.

Pascopella also reported that the San Diego school district had switched all their 9th graders to a physics course; requiring the retraining of 60 teachers to boost the number of physics teachers from 30 to 90. Also, "at the Hockaday School, an all-girls private K-12 school in Dallas, freshmen started taking physics last fall" (Pascopella, 2003, p. 5). In Maryland, four counties had switched to Physics First (including the county where the Paint Branch High School is located) and three others were considering the switch.

In September, 2003 the Biological Sciences Curriculum Study (BSCS) hosted a symposium to discuss the implications of the new science sequence with respect to biology. The proceedings were published in 2004 and include a series of presentations. Lederman stressed four goals for the new 9th grade physics course: the nature of science; the power of mathematics; the process of physics, storytelling; and conceptual understanding. With respect to mathematics he indicated that:

> Students should be able to appreciate the incisiveness of a mathematical statement, its power to predict the future of simple system (e.g. a ball rolling on a smooth level surface), and eventually, the value of

> mathematics in its role of the 'language of science.' Motivations like these must improve the learning of mathematics. (Lederman, 2003, p. 13)

At the BSCS conference Cheryl Mason, a biology teacher and past president of the National Association for Research in Science Teaching, described the advantages that would be obtained by the biology course if students had all studied physics and chemistry. For example, "having a basis for comprehending the complexities of the electromagnetic spectrum, the relationship between pressure and volume, energy conversion, and driving forces behind chemical reactions all would make for a richer course of study in biology at the 11^{th} grade level" (Mason, 2003, p. 54).

Michael Neuschatz, director of the American Institute of Physics's (AIP's) Nationwide Surveys of High School Physics Teachers, took a more cautious position. He expressed concerns with both a lack of physics teachers to support a reversal in the sequence as well as a generally negative view of the change by most physics teachers. He reported that in a 2001 poll it was found that; "as far as physics teachers' attitudes were concerned, we found a broad negative reaction to the idea [of reversing the sequence]. Overall, 61 percent of the teachers disagreed [with reversing the sequence], 40 percent strongly so….this is among the more one-sided results we have gotten on various opinion questions we have posed…" (Neuschatz, 2003, p. 58). He softened that a bit later by pointing out that among those teachers who were engaged in teaching 9^{th} grade physics "a solid majority preferred the restructured curriculum" (Neuschatz, 2003, p. 58). He seemed uncommitted to the new approach and inclined more towards a physical science course in 9th grade followed by biology in 10th grade. Students with a greater interest in science would then take more advanced courses. Partly, this seemed to reflect the belief that the interest and funding would not be available to support more than a two year science requirement.

Greenhalgh, reported on a Physics First program that had failed; at least it had failed in the sense that after five years the school decided to revert back to the traditional sequence. However, he was unable to explain why that decision was made, saying “it was unclear to me exactly what justification was at the crux of my colleagues’ votes” (Greenhalgh, 2003, p. 72). One problem was that there was no clear definition as to what would have constituted “success”. That remained subjective and “very little quantitative data was gathered, and less remains” (Greenhalgh, 2003, p. 71). He reported positive anecdotal evidence for the new sequence: students recognized and voiced appreciation of the new sequence; those in the new sequence “felt pity” for those still in the traditional sequence; greater coverage was achieved in chemistry; the 11th grade biology classes won the state environmental competition each of the four consecutive years they entered; the number of students taking physics increased; 11th graders outperformed 9th graders in their biology course.

Greenhalgh reported that the reasons given for going back to the traditional sequence were: 9th grade Honors Physics was not considered mathematically rigorous enough to prepare students for college physics; it was considered fraudulent to call that course “Honors Physics”; enrollments in the first and second year "regular" physics courses declined. Greenhalgh did not believe that any of these there were either sufficiently true or sufficiently significant to give up the advantages of the new sequence. However, he noted that in the five years during which the new sequence was in place that six of the nine teachers who had made the decision to switch to it had left the school, including the 9^{th} grade physics teacher. He attributes this "failure" to emotional and personnel reasons rather than problems with respect to student learning.

Legleiter (2003) reported on a successful transition to the new sequence in his high school, located in El Dorado, Kansas, which launched a 9^{th} grade conceptual physics course. The author did not report on the mathematics content of the course; however, it was taught based on a modeling approach. He reported that his students did well in "Physics Olympics" competitions where they faced teams composed of 11^{th} and 12^{th} grade students; some in AP physics courses. They also performed above average on the Kansas State Science Assessments; not only in physics, but also in biology.

Lederman's position with regard to the importance of mathematics in the 9^{th} grade physics course has continued to evolve. In a January, 2005 editorial he indicated that a key advantage of having the first high school course be physics was its relationship to mathematics:

> Early in physics we meet with definitions that are precise, e.g., position, velocity and acceleration. We learn the power of mathematics (Algebra I) to clarify the definitions and to enable us to make predictions: for example, $x = x_o + vt$ can predict where an object will be at some future time.

(Lederman, 2005, p. 6)

The idea that the new science sequence would be a benefit to mathematics achievement has re-emerged more strongly as the second, more recent, phase of the Physics First movement has evolved. In a May, 2005 editorial it was noted that one of the four advantages for the new sequence was that students will get to "apply their growing mathematical skills to solve real-world problems" (Ewald, Hickman, Hickman, & Myers, 2005, p. 319). Of the five indicators of the success of the program, in schools that are using it, one was "improved mathematics understanding and achievement" (Ewald, Hickman, Hickman, & Myers, 2005, p. 319). In response to the notion that 9th graders might not have the mathematics background to study physics, it was pointed out that "most eighth-grade students are now enrolled in Algebra I or have completed an integrated middle school mathematics program that includes much of the algebra that they will need to be successful in physics" (Ewald, Hickman, Hickman, & Myers, 2005, p. 320).

They also noted that other indicators of the success of this approach were that "students study more challenging science courses; improved scores on standardized tests including AP, SAT II, and state exams; enrollments that are move balanced by gender and race; and increased interest for careers in science, technology, and engineering" (Ewald, Hickman, Hickman, & Myers, 2005, p. 319).

There has been a dearth of quantitative studies on physics first program. One unpublished study, evaluated the effect of a 9th grade physics course on mathematics achievement (Glasser, 2005). The author used an 8th grade mathematics placement test to determine that entering 9th graders had statistically similar levels of achievement over a six year period. For the first three years of the study, 9th grade students were taught biology; for the following three years the 9th grade science course became physics. All students then took the PSAT in 10th grade. By comparing the PSAT scores in mathematics over that six year period the study showed that math achievement had improved. The significance of the study was less than .005 for the last two years of data and showed an improvement from 67.3 to 75.4, when comparing the first three years to the last two years (the transition year showed a similar but smaller effect). This represents an eight percent improvement that could plausibly be connected to the switch in science sequence. Of course, that cannot be proven since this does not qualify as an experimental setting. However, it is consistent with the hypothesis that 9th grade physics was beneficial to mathematics achievement.

I wrote an unpublished paper (Goodman, 2005) based on a series of individual and group interviews of students in my school. As I describe in greater detail below, that school had implemented a physics-chemistry-biology curriculum based on a mathematically intensive 9th grade physics course. That course's goal was not only to serve as a foundation for the succeeding science courses, but also to improve student achievement in mathematics. This was to be accomplished through the intensive use of algebra; a subject that all the students had studied, or were concurrently studying; no trigonometry was used as many of the students had not yet studied geometry.

The student interviews were used to identify if students perceived that the physics course had a beneficial effect on their mathematics achievement and, if so, why? It was found that while all the students felt that physics had benefited their understanding of mathematics, the reasons given fell into three distinct categories: those with weak prior math achievement felt that physics gave *meaning* to mathematics; those with strong math backgrounds felt that physics gave them an opportunity to *practice* their math skills; those with moderate prior math achievement indicated that physics made math seem *useful*. The correlation between student achievement in mathematics and the benefit they identified due to the physics course had a Pearson correlation of 0.765 and a significance of less than 0.01. The terms used by the students; *meaning, usefulness and practice*, will be critical to the theoretical framework for the program under study.

The question of the order in which the sciences should be taught extends at least back to the Committee of Ten in 1892. Even that committee never reached consensus: the overall committee recommended physics-chemistry-biology and the science subcommittee, which prevailed, chose biology-chemistry-physics. The controversy is fundamental in nature: the science content leads one to physics-chemistry-biology but the math required for the first year course leads to the reverse. There is a tension between the mathematics content and the physics content of any proposed first year physics course. The recent evolution in the curricula of those courses is an attempt to resolve that tension: an attempt that is now, more than 100 years after the initial decision regarding the sequence, proving successful.

Perception and Cognition

One reason that science and mathematics have become such high priorities for countries around the world is that they represent useful descriptions of the universe and how it works. By necessity, any such description is constrained by the limits of our perception and cognition. These limitations are unavoidable; they result from the vastness and complexity of the universe.

The universe is filled with a plethora of information; too much for any species to process and understand. For example, we are awash in a broad spectrum of electromagnetic radiation ranging in wavelength from below 10^{-12} m to above 10^{5} m. Visible light, while critical to our survival, represents just a tiny sliver of that spectrum. The vast majority of the electromagnetic spectrum is invisible to us. This perceptual limitation does not just apply to our vision, it holds for all our senses.

Even given the limits of our senses, there is too much information to consciously process. Vygotsky (1987b) wrote of the problem of constancies: "why white looks white even in shadow, a dinner plate circular even at an angle, why people, for example, do not seem to change size as drastically as the size of their retinal images in our eye when they walk away from us, etc." (Bruner, 1987, p. 8).

If you look at a circular tabletop from directly above, it is clearly a circular. However, from any other angle it would be seen as one of an infinite set of possible elliptical tables. If each time we saw that table from a different angle we had to consciously figure out its shape, that set of decisions would fully occupy our minds. In fact, we do not need to make a conscious calculation; that calculation is done at a pre-conscious level. This is not a simple trick, as someone designing a computer system to interpret the output from a video camera would tell you; but it is one of many thousands of pre-processing steps that our brains do for us each moment.

That pre-processing is not consciously accessible to us and, as a result, represents both a valuable tool and a constraint on what we can perceive. “The visual world is not a faithful reflection of the images on the retinas of our eyes but a world somehow constructed out of such images” (Gregory, 1988, p. 1). In fact, most of our thought processes are inaccessible to us. “Perhaps the most fundamental, and initially startling, result in cognitive science is that most of our thought is unconscious – that is, fundamentally inaccessible to our direct, conscious introspection” (Lakoff & Nunez, 2000, p. 27). Or as Hofstadter put it, “We can liken real-world thought processes to a tree whose visible part stands sturdily above the ground but depends vitally on its invisible roots which extend way below ground, giving it stability and nourishment. In this case the roots symbolize complex processes which take place below the conscious level of the mind – processes whose effects permeate the way we think but of which we are unaware” (1989, p. 569)

As a result of innate sensory limitations and unconscious cognitive processing, children are not blank slates who absorb information about the world directly. Rather, each child's brain processes the input from their circumscribed senses in such a way that they perceive the world in an organized manner. Kant (1781) pointed out that that organization is accomplished through the creation of categories within which our perceptions are automatically sorted. "Kant's conclusion was that the mind must not be a totally blank slate. It must come accessorized with certain 'categories', like causality, that organize experience for us. And the raw phenomena of the world must themselves be knowable only insofar as they conform to this way of being organized" (Menand, 2001, p. 263). Or as Vygotsky said, "…all human perception consists of categorized rather than isolated perceptions" (1978, p. 33).

More recently, Pinker pointed out that "…probably all science and mathematics is driven by intuitions coming from innate modules like number, mechanics, mental maps, even law. Physical analogies (heat is a fluid, electrons are particles), visual metaphors (linear function, rectangular matrix), and social and legal terminology (attraction, obeying laws) are used throughout science" (Pinker, 2000, p. 444). Similarly, diSessa and Sherin developed their theory of coordination classes from that same foundation: "…seeing is a substantial accomplishment of learning and will depend only very partially on basic perceptual capabilities" (diSessa & Sherin, 1998, p. 16).

While the above argument has been developed for humans, the same requirement for sensory censorship and pre-processing exists for all species. To believe otherwise would presume that the brains of other species are capable of handling vastly more sensory input and conscious cognition than are our own.

As that does not seem reasonable, it is to be expected that these characteristics are not unique to man.

> *Koffka sees in structures some primary, primordial, and essentially primitive principles of behavioral organization.* [According to him] It would be a mistake to think that this principle applies only to higher or intellectual forms of activity. It is also present in the earliest and most elementary forms of development. This debate, says the author, confirms our understanding of the primitive nature of structural functions. If the structural functions are really so primitive, they must appear in the primitive behavior that I call instinctual. We see how in refuting the theory of trial and error learning Koffka was led to the conclusion *that we can apply the structural principle equally to the higher intellectual actions of human-like apes, as well as to the training of lower mammals in Thorndike's experiments, and finally to the instinctual reactions of spiders and bees.* (Vygotsky, 1982a, pp. 245-246). (Wertsch, 1985, pp. 21-22)

The understanding of our perception and cognition has profound implications for science education. The goal of science education cannot be to alter the deep cognitive structure of students. Our goal must be to embrace and understand those perceptual structures and use them as a foundation upon which to construct an understanding of the world that transcends them. While, over extended lengths of time, students may develop new intuitions about pieces of the world that they extensively study; making that the goal of science education would require an undue amount of time for the benefit that would result; certainly for students who have not already committed themselves to careers in science.

While human are not able to change their perceptual and cognitive structures; they have been able to develop mediational tools that stand between themselves and the world in order to interact with the world more effectively. We are uniquely capable of being able to improve those tools and pass them along to succeeding generations. Through this process we humans have achieved a pace of sociocultural evolution that has vastly exceeded the pace of our biological evolution.

Tools of Mediation and their Evolution

Humanity's explosive sociocultural development over the last thousands of years was not due to the ongoing biological evolution of the human brain; the speed of our advance has been too rapid for biological evolution to have kept pace. More importantly, our sociocultural differences from people a few thousand years ago are large while our biological differences are not. When we read authors from 2000 to 3000 years ago, we hear voices that are very much like ours. Their perceptions and the manner with which they express themselves are very familiar, as familiar in many ways, as reading contemporary authors from different cultures. We certainly do not get the impression that we are hearing from a different biological species. However, the lives of those ancient authors were vastly different from ours, as was their understanding of the world. The lives and understandings of humans have evolved dramatically while they have not evolved very much, if at all, biologically.

> There is no reason to believe that the human brain of one or even two thousand years ago was dissimilar to ours; yet there is an enormous disparity between modern *culture* and that of previous millennia. This pace of change is much too rapid to be picked up at the level of the genes, so if evolutionary theory is to be applied to such changes, then it will be more appropriate to bring it to bear on behaviour and the mind rather than on neural architecture and its genetic code" (Distin, 2005, p. 15)

The evolution of mediational tools represents the fundamental explanation of human's rapid progress. Mediational tools represent techniques that allow people to externalize their internal thought processes in ways that allow them to control their interactions with the environment. The creation of tools and signs, mental tools, represent key forms of mediation. Rather than interacting directly with the environment; tools are developed that stand between the person and the environment; the person interacts with the tool and the tool interacts with the environment. Thoughts and designs that begin internally are expressed externally through these tools: tools that mediate the interaction between the person and the world.

Mankind's rapid progress in the past thousands of years has been dominated by the evolution of mediational tools. "The special quality of the human environment is that it is suffused with the achievements of prior generations in reified (and to this extent materialized) form" (Cole & Wertsch, 2005, p. 2). Where millions of years might be required for the evolution of a wing, an opposable thumb or a claw, only a relatively brief time was required for the invention and evolution of a hammer, a spear or a shovel. The term "evolution" is appropriate here because of the way tools pass from generation to generation with improvements being retained and mistakes being eliminated: each improved new tool becomes part of mankind's heritage. Useful tools spread through a version of natural selection and survival of the fittest. Better tools were reproduced and improved while weaker tools were not. Successful tools become common ancestors to later tools, which branched off to form their own clades.

The same principle of cladistics that has been developed to study biological evolution is applicable to tools. One can imagine a primordial garden implement in the distant past branching into rakes, shovels and hoes; then each of those branching into different specific types such as lawn rakes; soil rakes; coal shovels; snow shovels; etc. Each tool that we see around us today had an evolutionary past that reaches back to a set of common ancestors. While there may have been independent inventions of many of these tools, the same is true of biological evolution. Dawkins pointed out that, "…it has been estimated that 'the eye' has evolved independently more than 40 times in various parts of the animal kingdom" (Dawkins, 2004, p. 388). That does not argue against biological evolution anymore than the parallel case argues against the evolution of mediating tools.

The process of biological evolution is based on the interaction of phenotype, genotype and the environment. The process of tool evolution is based on the interaction of design, society and the environment. Without the genotype, each biological innovation would be a dead end: a mutation might lead to a beneficial phenotype, but without the ability for it to be passed onto the next generation each successful mutation would have to be chanced upon again and again. Evolution would be more like Brownian motion, a drunken man's walk, than progress.

Similarly, without a society to pass along the improvements it has made in its tools; each improvement would have to be recreated every generation: there would be no progress. The fact that each society passes along its own innovations, in addition to those of its predecessor societies, is fundamental to human culture. It has created a distinct stream of cultural evolution that moves so rapidly that it makes biological evolution look like it is standing still. "Most of what is unusual about man can be summed up in one word: 'culture'. I use the word not in its snobbish sense, but as a scientist uses it. Cultural transmission is analogous to genetic transmission in that, although basically conservative, it can give rise to a form of evolution" (Dawkins, 1999, p. 189).

The importance and uniqueness of the evolution of mediational tools is fundamental but rarely noted. We all know that once a device has been created, it improves with time, whether it is the bicycle, computer or baby stroller. Once a new tool clade has been formed, rapid evolution occurs as humans refine the new tool even while that tool simultaneously branches in multiple directions: certain designs become dead ends while others prosper. This is out of the control of any individual: only the interaction of society, the devices and the environment can "pick winners". Sometimes the winners are not what would be analytically considered the best design. People still argue about the internal versus external combustion engines; Betamax versus VHS video recorders; or Apple versus PC computers. But no individual can choose which design will win; that naturally evolves through the interaction of the design, society and the environment.

Tool evolution separates mankind from all other species. While it is true that tool use does occur to an extent in some other species, that is a relatively minor feature of those species and does not show the characteristics of rapid evolution described above. “No other tool-using animal on Earth has demonstrated the ability to create and retain innovations in their use of tools” (Kurzweil, 1999, p. 14). Our ability to evolve tools helps defines our species: it has led mankind to dominate this planet: no other species even comes close to man in this respect.

All tools are to some extent mental tools in the sense that they are used and passed down by society and they evolve through the interaction of the individuals in those societies with their environment. The use of these tools requires the education of novices by more experienced teachers and improvements must first be conceived and communicated before they are incorporated and applied.

Through this process it was only natural that truly psychological tools, signs, emerged: language; writing; mathematics; science; money; commerce: etc. The emergence and evolution of these mental tools has driven, and continues to drive, the cultural evolution of mankind. “The natural line of development is generally associated with elementary mental functions, and the cultural line with higher mental functions. Furthermore, natural development is explained primarily on the basis of biological principles, whereas cultural development is attributed to principles that apply to mediational means, including the principle of decontextualization" (Wertsch, 1985, p. 42).

Mental tools represent a clade of their own. They began as part of the process of developing physical tools but were then taken out of that context, decontextualized, to become tools in their own right. As with all tools, each mental tool proceeds through its own evolution. For example, oral language led to written language which then evolved to the wide variety of written forms that language now takes: stories; novels; novellas; science papers; term papers; poetry; journals; notes; blogs; etc. Human society drives the evolution of these mental tools by means of cultural natural selection.

While people use physical tools to change the external world, mental tools change the way that we perceive the world, the way we think and the way we communicate. Acquiring a mental tool transforms the learner and their relation to society. "Vygotsky argued that a sign [a psychological tool] changes nothing in the object of a psychological operation. A sign is a means of psychologically influencing behavior – either the behavior of another or one's own behavior; it is a means of internal activity, directed toward the mastery of humans themselves. A sign is inwardly directed' (ibid.)" (Wertsch, 1985, p. 78)

Developing learners by teaching them mental tools is a primary goal of education. Newly acquired mental tools do not replace the biological foundation of a learner's thinking, but overlays that foundation in a way that allows the tool's acquirer to be more effective.

> Vygotsky did not view the introduction of a new form of mediation as resulting in a form of functioning in which factors that had previously governed psychological functioning no longer operate. The point is always that the explanatory framework must be *reformulated*, not discarded and replaced, in order to take into account a new factor and its interactions with existing factors. For example, with the introduction of psychological signs in social history, the biological constitution of the organism that has resulted from evolution continues to play an important role, but psychological functioning is now governed by biological constitution *and* sign use. (Wertsch, 1985, p. 23)

Physical and psychological tools allow us to modify our physical and social environment, but by their very use they modify the way we perceive those environments: they change us. It has been said that when you give a child a hammer, all the world becomes a nail. In a very real sense, that is true of all of us. Each new tool modifies our view of the world and our role within it; "…the psychological tool alters the entire flow and structure of mental functions. It does this by determining the structure of a new instrumental act, just as a technical tool alters the process of a natural adaptation by determining the form of labor operations (Vygotsky, 1981a, p. 137)" (Wertsch, 1985, p. 79)

The creation of physical tools, and our ability to drive their evolution, represented a significant turning point in man's history; but linked with the advent of mental tools they drove an explosive advance in human culture that remade the arc of human history. Cole and Scribner point out that, "like tool systems, sign systems (language, writing, number systems) are created by societies over the course of human history and change with the form of society and the level of its cultural development. Vygotsky believed that the internalization of culturally produced sign systems brings about behavioral transformations and forms the bridge between early and later forms of individual development" (1978, p. 7)

The development and evolution of mediational tools is a defining characteristic of our species. While these began as physical tools, their use and evolution required the development of psychological tools: those psychological tools were then subject to the same evolutionary forces. Our cultural heritage represents the cumulative total of all the tools that have been developed, improved and passed along by prior generations. They represent a key element of human progress. The medium of biological evolution is DNA: the medium of tool evolution is society. A vital role of society is to improve and pass along tools from one generation to the next. As our tools became increasingly complex institutions were developed to expedite their transmission: educational institutions.

The Role of Education

Education plays a critical role in the development of both mankind and the individual. It teaches children how to apply a wide range of tools and signs that have been developed over thousands of years. If each child had to discover and develop these tools on its own, the explosive growth in human competence could not have occurred. This is true for two reasons. First, if each generation had to discover each tool and sign anew, then mankind would not advance, it would simply repeat the steps taken by its ancestors. Second, many of our tools and signs are shared within society and cannot be independently invented. For instance, a language must be shared within a community; it cannot be independently invented by individuals and retain its usefulness.

> There are two senses in which Vygotsky considered psychological tools to be social. First, he considered psychological tools such as ‘language; various systems for counting; mnemonic techniques; algebraic symbol systems; etc.’ to be social in the sense that they are the products of sociocultural evolution. Psychological tools are neither invented by each individual nor discovered in the individual’s independent interaction with nature. Furthermore, they are not inherited in the form of instincts or unconditional reflexes. Instead, individuals have access to psychological tools by virtue of being part of a sociocultural milieu. The second sense in which Vygotsky viewed psychological tools as social concerns more the ‘localized’ social phenomena of face-to-face communication and social interaction. Instead of examining forces that operate on a general sociocultural level, the focus here was on the dynamics that characterize individual communication events. Of course the two types of phenomena are not unrelated. However, they are governed by different explanatory principles and therefore require separate analyses. (Wertsch, 1985, p. 80)

The education of a child in the use of sociocultural tools is a key goal of education and occurs within a social context, as that is the context within which these tools were created. “By means of words children single out separate elements, thereby overcoming the natural structure of the sensory field and forming new (artificially introduced and dynamic) structural centers. The child begins to perceive the world not only through his eyes but also through his speech. As a result, the immediacy of ‘natural’ perception is supplanted by a complex mediated process; as such, speech becomes an essential part of the child’s cognitive development” (Vygotsky, 1978, p. 32).

The process of internalization of these mediational tools is critical to the education of the child. Through this process the development of the child is advanced by his or her education.

> The process of internalization consists of a series of transformations:
>
> (a) *An operation that initially represents an external activity is reconstructed and begins to occur internally.* Of particular importance to the development of higher mental processes is the transformation of sign-using activity, the history and characteristics of which are illustrated by the development of practical intelligence, voluntary attention, and memory.
>
> (b) *An interpersonal process is transformed into an intrapersonal one.* Every function in the child’s cultural development appears twice: first on the social level, and later, on the individual level; first *between* people (interpsychological), and then *inside* the child (*intrapsychological).* This applies equally to voluntary attention, to logical memory, and to the

> formation of concepts. All the higher functions originate as actual relations between human individuals. (c) *The transformation of an interpersonal process into an intrapersonal one is the result of along series of developmental events".* (Vygotsky, 1978, p. 57)

Vygotsky's stressed the relationship between everyday and school experiences. Everyday experiences are those that the child has outside of an educational setting. School experiences are mediated by social constructs that allow the child to transcend the level of understanding that they would have obtained on their own. The educational experience is the reason that a modern child has an understanding of the world that is so significantly different than that of a human child 5000 years ago. "To imagine that socially constructed knowledge in areas like science, technology or mathematics is everyday knowledge is to misunderstand the purpose of schooling, which is the pupil's initiation into grappling with the theoretical objects of these domains" (Bliss & Askew, 1996, p. 60).

Education starts with the everyday understanding that the child brings to school and advances and changes that understanding through the development of mediational signs and tools that are not part of the everyday experience. "Tharp and Gallimore (1988 a, b) propose that teachers should act to 'weave together everyday and schooled understanding'. The skilled teacher brings, or weaves, together pupil perspectives and understandings with those that she seeks to promote in the classroom. This process builds upon pupil prior knowledge and understanding with the ideas and concepts the teacher wishes to explore with them" (Daniels, 2001, p. 117).

Education does not occur in a vacuum. The child's exposure to the world, including their family, friends and society, prior to attending school begins to activate the categories that are an innate part of their brains while also beginning the development of signs and tools. The school must meet the child where he or she is upon entering and then work with them to teach them the sociocultural signs that allow them to build on and transcend what they have already learned. A theoretical understanding is built on top of the categorizations, signs and tools with which the child enters school.

> That children's learning begins long before they attend school is the starting point of this discussion. Any learning a child encounters in school always has a previous history. For example, children begin to study arithmetic in school, but long beforehand they have had some experience with quantity – they had to deal with operations of division, addition, subtraction, and determination of size. Consequently, children have their own preschool arithmetic, which only a myopic psychologist could ignore. (Vygotsky, 1978, p. 84)

Education plays a fundamental role in the transmission of mental tools from generation to generation. It is certainly not to be expected that any child will discover these tools; it that were possible children would have discovered them millennia ago. The idea that students will "discover" mediational tools misunderstands the very nature of tool evolution and the role of education.

The cultural heritage of our mediational tools represents our rightful inheritance; an inheritance that has been improved and passed along by all who came before us. Creating the conditions by which mediational tools may be successfully passed on to the next generation is the role of education: that is why education is central to human society. However, the process of passing those tools along is not as simple as simply explaining them; students must be helped to construct them.

Social Constructivism

Mediational tools, including the tools of mathematics and science, were developed in a social environment and that is the environment in which they are most easily and efficiently learned. The acquisition of these tools advances the development of the child by separating them from their everyday understandings: a separation that Vygotsky viewed as the key role of science education.

Vygotsky saw the teacher as playing an important role in the social group in which the mediational tool of science is developed: instruction would take many forms but would primarily consist of discourse between the students and the teacher and between the students themselves.

> '[Vygotsky] wrote about collaboration and direction, and about assisting children 'through demonstration, leading questions, and by introducing the initial elements of the task's solution' (Vygotsky, 1987, p. 209), but did not specify beyond those general prescriptions. Nevertheless, he considered what we would now call the characteristics of classroom discourse (see Cazden, 1988) as central to his analysis. Vygotsky (1981) claimed that

> the intellectual skills children acquire are directly related to how they interact with others in specific problem-solving environments. He posited that children transform the help they receive from others and eventually use these same means to direct their subsequent problem-solving behaviors (Diaz, Neal, & Amaya-Williams, this volume). Therefore, the nature of social transactions is central to a zone of proximal development analysis (Moll, 1989; Tudge, this volume). (Moll, 1990, p. 11)

While this social constructivist approach welcomes the teacher to the social group within the classroom, it rejects the use of direct instruction in a lecture form.

> Pedagogical experience demonstrates that direct instruction in concepts is impossible. It is pedagogically fruitless. The teacher who attempts to use this approach achieves nothing but a mindless learning of words, an empty verbalism that stimulates or imitates the presence of concepts in the child. Under these conditions, the child learns not the concept but the word, and this word is taken over by the child through memory rather than thought. Such knowledge turns out to be inadequate in any meaningful application. This mode of instruction is the basic defect of the purely scholastic verbal modes of teaching which have been universally condemned. It substitutes the learning of dead empty verbal schemes for the mastery of living knowledge. (Vygotsky, 1987a, p. 180)

But Vygotsky did not discourage teachers from directly explaining concepts and ideas to their students at the appropriate times. He felt that an explanation at the blackboard by a teacher might be very effective when assisting a student who is struggling to learn a challenging new concept. However, the student must be engaged in problem solving and the instructional help must be at the appropriate level.

> Recently psychologists have shown that a person can imitate only that which is within her developmental level. For example, if a child is having difficulty with a problem in arithmetic and the teacher solves it on the blackboard, the child may grasp the solution in an instant. But if the teacher were to solve a problem in higher mathematics, the child would not be able to understand the solution no matter how many times she imitated it. (Vygotsky, 1978, p. 88)

This discourse must be ongoing and between not only the teacher and a student but also and between the students themselves; until everyone in the class understands the concept. Davydov explains the challenges that a teacher faces and makes it clear why no formulaic perspective towards teaching is effective.

> The teacher's work is particularly complex because, in the first place, the teacher must be well oriented to the regularities of the child's personal activity, that is, know the child's psychology; in the second place, the teacher must know the particular social dynamics of the child's social setting; and in the third place, the teacher must know about the possibilities of his or her own pedagogical activity to use these sensibly and thus raise to a new level the activity, consciousness, and personality

> of his or her charges. This is why the work of a genuine teacher can never be stereotyped or routine; the teacher's work always carries a profoundly creative character. (Davydov, 1995, p. 17)

Daniels points out why one needs to be wary of "authentic problems" as they can move the student towards "everyday experience" and away from the structured learning that represents the essential value of learning science.

> This question of authenticity seems to raise key problems. Vygotsky's distinction between the everyday and the scientific would lead to the suggestion that if 'authentic' problems in 'authentic' settings' are to form the content of a curriculum then they should be selected very carefully. Following Davydov and Kozulin they should be problems which lead to theoretical learning…. The cognitive apprentice approach opens the question of the relationship between the schooled and the everyday and yet seems to close the question by attempting to place the schooled in the everyday. This seems to ignore the suggestion that schooling may be capable of helping to transcend the constraints of the everyday. (Daniels, 2001, p. 116)

Once mental tools are acquired, they are used to learn higher level mental tools: in the process, they become incorporated into the learner; they become automatic. "The development of our species, let alone the individual's development, surely requires that certain actions and procedures be carried out nonreflectively and without any appreciation of the meaning or explanation of the action" (Murray & Sharp, 1986, p. xi). Through use and practice the tool becomes part of the learner and allows the learner to move beyond it. In this manner, algebra becomes part of the cognition of the learner as it is applied to solving physics problems; chemistry becomes incorporated as it is used to understand biology problems; etc. The learner uses and goes beyond the algebra or the chemistry and, as a result, the algebra or the chemistry becomes part of their basic understanding.

In the following story, Leont'ev makes an important point that is directly relevant to this study. He describes how in the process of learning to drive a car the skill of shifting gears is initially a significant challenge and, to some extent, an end in itself: it must be consciously learned. However, even as that mental tool is being acquired, it changes from being an end to a means. It is needed in the actual driving of the car, but as the driver moves on to other challenges, fades into the driver's subconscious.

> Initially every operation, such as shifting gears, is formed as an action subordinated specifically to this goal and has its own conscious 'orientation basis. Subsequently action is included in another action… for example, changing the speed of the car. Shifting gears becomes one of the methods for attaining the goal, the operation that effects the change in speed, and shifting gears now ceases to be accomplished as a goal-oriented process: its goal is not isolated. For the consciousness of the driver, shifting gears in normal circumstances is as if it did not exist. He does something else: he moves the car from a place, climbs steep grades, drive the car fast, stops at a given place, etc. Actually this operation [of

> shifting gears] may, as is known, be removed entirely from the activity of the driver and be carried out automatically. Generally, the fate of the operations sooner or later becomes the function of the machine. (Leont'ev, 1978, p. 66)

Applying previously learned information, such as how to shift gears in a car, to more complex problems, like how to drive up a hill to get to a specific location, is a critical part of learning. If problems never become more complex, what was learned earlier represents becomes a dead-end; its value is never reinforced; it is never shown to be useful. Also, the ability to solve more complex problems is never developed; the ability to solve even simple problems weakens through disuse. Solving more complex challenging problems is critical for learning.

This can be seen in the case of the students enrolled in the Rutgers Astrophysics Institute (Etkina, Matilsky, & Lawrence, 2003) they were not learning to shift gears and drive cars to remote locations; but they were learning to use the mediational tools of science and mathematics to solve complex problems involving real data; in the process of doing that, they acquired the mediational tools of mathematics and science. The Institute is a summer program for advanced science students who conduct genuine research based on live data from X-Ray telescopes. Etkina et al. found that students made substantial gains in their understanding of complex physics concepts by using those concepts to analyze data and solve problems.

The program design involved a number of factors which may have contributed to its success. While much of the focus of their study was on the value of using authentic data to develop and test hypotheses: a second key factor was the significant amount of group work that was involved over an extended period of time. "'Understanding and progress in science is best viewed as constructed knowledge within communities of knowers' (Hawkins and Pea, 1987 p. 292). RAI strongly emphasized the collegiality of science. During the summer students worked in groups of 4 – 6. By the end of the summer each student had worked with every other student" (Etkina, Matilsky, & Lawrence, 2003, p. 964). The authors cited two implications from their study.

- The value of the fact that "(a) students use experimental evidence to construct explanation (models) and then test them by predicting the results of new experiments, and (b) students use the same approach…to investigate new phenomena using real-time data. (Etkina, Matilsky, & Lawrence, 2003, p. 981)
- They [Students] no longer fear complex problems and do not perceive the teacher as an authority. This result might be because students were given plenty of time to work on complex tasks. (Etkina, Matilsky, & Lawrence, 2003, p. 981)

While these two factors are inseparable in the cited study as both were present throughout, my study focuses on the effect of the second factor. The use of real data probably serves as a motivation to students to engage in group problem solving that advances their development. But, the proximate cause for their learning is the group problem solving process itself. A very important factor is the amount of time that was given for the group to work on problems without the intervention of an outside authority. Any such intervention would have cut short the development of the students. Under time constraints group collaboration breaks down.

This same process of learning through problem solving can be seen in a mathematical context. Schoen and Charles point out that the "key to fostering students' understanding is engaging them in trying to make sense of problematic tasks in which the mathematics to be learned is embedded" (2003, p. xi). Hiebert and Wearne add to this that, "The key to allowing mathematics to be problematic for students is for the teacher to refrain from stepping in and doing too much of the mathematical work too quickly. But students must serve their role as well. They must see something as problematic that they want to resolve" (2003, p. 7). Together these two statements prescribe the same approach for learning mathematics as is used in the RAI for learning physics.

Heller studied the effect of group problem solving in two contexts: a freshman university course (Heller, Keith, & Anderson, 1992) and a sophomore community college modern physics course (Heller & Hollabaugh, 1992). In both cases, problem solving strategies were taught to students by challenging them with complex problems; problems that were designed to be different than typical back-of-textbook problems in that they did not explicitly identify the unknown variable; provided too much information; left out information that was externally available; and required that reasonable assumptions be made. The studies found that all students gained through the group work, regardless of their initial ability; that group solutions were superior to individual solutions, no individual could match the performance of the group of which he or she was a part; and it was easier for instructors to teach in this structure than in a traditional class.

Educational tools were developed, improved and can efficiently be passed along to the next generation in a social context: they will not be discovered by students on their own without the help of a teacher; they are very ineffectively transmitted by lecture; and they are reinforced by being actively used to solve problems. Problem solving serves both as a medium in which prior tools are used, and thereby shown to be useful, and in which new tools are developed. Since usefulness is a driver of both tool construction and evolution, it is a critical element in the educational process. A rich problem solving environment, maintained by an actively involved teacher, promotes student learning.

The Zone of Proximal Development

Vygotsky strongly felt that education must advance development, not wait upon it. While Piaget felt that education must wait until the child reached a stage of development where they were prepared to learn a concept, Vygotsky felt that "learning which is oriented towards developmental levels that have already been reached is ineffective from the viewpoint of a child's overall development. It does not aim for a new stage of the developmental process but rather lags behind this process. Thus, the notion of a zone of proximal development enables us to propound a new formula, namely that the only 'good learning' is that which is in advance of development" (Vygotsky, 1978, p. 89).

Vygotsky defined the zone of proximal development as "…the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers" (Vygotsky, 1978, p. 86). He saw advancing the development of the child as the key goal of education.

Vygotsky viewed education as a fundamentally social process since the mediating tools that are taught in school are fundamentally social to begin with and their effect is to advance the development of the child as a member of society.

> We propose that an essential feature of learning is that it creates the zone of proximal development; that is, learning awakens a variety of internal developmental processes that are able to operate only when the child is interacting with people in his environment and in cooperation with his peers. Once these processes are internalized, they become part of the child's independent developmental achievement. From this point of view, learning is not development; however, properly organized learning results in mental development and sets in motion a variety of developmental processes that would be impossible apart from learning. Thus learning is a necessary and universal aspect of the process of developing culturally organized, specifically human, psychological functions. (Vygotsky, 1978, p. 90)

The very mediational tools that make us more effective in our interactions with the world also change us in fundamental ways; mediation is a two way street. Signs begin in the external social world, become internalized and finally modify the way that we think. As Vygotsky said, “any higher mental function necessarily goes through an external stage in its development because it is initially a social function. This is the center of the whole problem of internal and external behavior… When we speak of a process, “external means social.” Any higher mental function was external because it was social at some point before becoming an internal, truly mental function. (1981b, p. 162)” (Wertsch, 1985, p. 62).

Bruner (1987) stresses the role that dialogue with a more expert teacher plays in the development of understanding on the part of students in their ZPD. “Once a concept is explicated in dialogue, the learner is enabled to reflect on the dialogue, to use its distinctions and connections to reformulate his own thought” (Bruner, 1987, p. 4).

Thus, education transforms students not by teaching them a set of facts but by advancing their development while passing along to them the mediational signs and tools that are their inheritance as members of human society. This is efficiently accomplished in a social environment: the type of environment in which those tools and signs were developed and evolved. This instruction “calls to life in the child, awakens and puts in motion an entire series of internal processes of development. These processes are at the time possible only in the sphere of interaction with those surrounding the child and in collaboration with companions, but in the internal course of development they eventually become the internal property of the child. (Vygotsky, 1956, p. 450)" (Wertsch, 1985, p. 71).

While Vygotsky's perspective on the importance of the social interaction in the development of the child is often contrasted with Piaget's emphasis on the individual, this difference is perhaps exaggerated. Cole and Wertsch point out that Piaget also recognized the importance of social interactions in individual development. "'There are no more such things as societies qua beings than there are isolated individuals. There are only relations….and the combinations formed by them, always incomplete, cannot be taken as permanent substances' (Piaget, 1932, p. 360) and '...there is no longer any need to choose between the primacy of the social or that of the intellect: collective intellect is the social equilibrium resulting from the interplay of the operations that enter into all cooperation (Piaget, 1970, p. 114)'" (Cole & Wertsch, 2005, p. 1).

An effective educational environment should maintain students in their zone of proximal development. In the context of a physics or mathematics class, this zone becomes defined as the difference between the most difficult problems that a student could successfully solve alone and the most difficult problems that he or she could solve by working with others or with the help of a teacher.

Maintaining each student in their zone of proximal development for the maximum amount of the time that they are in class is a difficult but important instructional objective. This zone is unique for each student, so this requires confronting students with a set of rich problems that they can solve together in a manner that each of them is challenged and engaged. It requires supplying just the right amount of information to keep the group moving forward, but no more than that. Too little or too much help work equally towards taking students out of their ZPD.

One of the reasons that it is possible to maintain everyone in their own ZPD while solving problems in common is that the more advanced students carry the additional burden of having to help the less advanced students construct their understanding; this requires a deeper level of understanding on the part of the advanced student than would otherwise be obtained and adds both their challenge and their achievement.

When students are in their ZPD, their learning is rapid and their attitude is positive. They not only enjoy solving the problems, they feel the joy of growing and becoming more effective. Students in this zone can be pictured as riding a wave. If they fall behind it, because the problems are too easy, they get bored and do not progress. If they get ahead of it, the problems are beyond the group's ability; they get overwhelmed, become frustrated and give up. But if the problems keep the students just at the edge of their ability, it is exciting to watch how quickly they progress.

Science: A Clade of Mediational Tools

Science can be viewed as the clade of mental tools that mediates between Man and the universe. The human endeavor of science represents the evolution of the mediational tools that were developed and improved upon by generations of individuals in order to understand our world. On the one hand, Man can only conceptualize as a species what a human can conceptualize as an individual: the cognitive abilities of individual humans will always constrain us. On the other hand, Man continues for millennia while individuals have just a brief lifetime. Ideas evolve over the course of generations; but they are still constrained by the cognitive limitations of the species.

> Pascal had compared the human race to a man who never dies, always gaining knowledge, while Leibniz spoke of the Present big with the Future. Turgot...[wrote that] ‘the human race, observed from its first beginning, seems in the eyes of the philosopher to be one vast whole, which like each individual in it has its own infancy and its own conditions for growth.’ Kant, in 1784 expressed the germ of the same concept, observing in particular that man’s rational dispositions are destined to express themselves in the species as a whole, not in the individual. (Wilson, 1998, pp. 21-22)

From this perspective, a scientific concept must have meaning for the person using it and must make predictions or statements about the world that are useful to that person. Without meaning, the person could not apply the concept. Without usefulness the tool would have no value. Tools without meaning or use are not selected for ongoing refinement through sociocultural evolution. That process of ongoing refinement is necessary for science to progress.

In this case, the term “useful” can be with respect to the world itself or in mediating between other theories or explanations about the world. While science began through the need to make predictions about the world around us, it has evolved and become decontextualized in the sense that many scientific concepts make predictions that have no direct use except in how they relate to other scientific predictions; they are useful in creating a self-consistent scientific view of the world. While a particular scientific concept might not have any direct immediate use; the scientific paradigm that it helps support might be very useful.

For instance, cosmological explanations for the origin of the universe cannot be said to make predictions that are directly useful to mankind, but they can predict consequences with respect to our current theories about how the world works that are useful to developing a useful scientific paradigm. They become an important part of science because of their usefulness within the structure of science itself.

While this approach towards the nature of science will be used in this study, it is worth exploring some other approaches because some of these alternative definitions of science may be isomorphic with the cladistics perspective.

Empiricism attempted to restrict scientific statements to direct experience. As Popper indicated, "…the fundamental thesis of empiricism [is that] experience alone can decide on the truth or falsity of scientific statements" (2002, p. 20). However, that approach is unrealistic in two key senses. First, as discussed above, our ability to "experience" is severely limited by our senses and by the cognitive categories that are pre-programmed into our perceptions. Without depending upon mediational tools to extend our understanding beyond the directly observable we would have an entirely constricted and not particularly useful view of the world. Secondly, because of "Hume's realization of the inadmissibility of inductive arguments" (Popper, 2002, p. 20) it is impossible to extend empirical observations to general theories. This failure of induction is due to the fact that what has happened in the past cannot be depended upon to determine what will happen in the future. "Hume has shown, I think conclusively, that induction is invalid…" (Popper, 1979, p. 272).

Logical positivism led to the belief that there is an underlying "scientific thought process", often described as the "scientific method", involving an iterative process comprised of hypotheses, predictions and experiments. Popper was skeptical that any such scientific method exists stating that, "if anyone should think of scientific method as a way which leads to success in science, he will be disappointed….Should anybody think of scientific method, or of *The Scientific Method*, as a way of justifying scientific results, he will also be disappointed" (1979, p. 265).

To the extent that a unique form of scientific reasoning, such as the scientific method, exists, that would not conflict with a cladistics view of science. That would simply designate that method as either defining the science clade or being a branch of it. In fact, science is much broader than any one method and, to the extent that a scientific method exists, the clade representing science would include it.

Kuhn made the case that there are really two types of science, normal science, "research based on one or more past scientific achievements" (1970, p. 10) and revolutionary science, "those non-cumulative developmental episodes in which an older paradigm is replaced in whole or in part by an incompatible new one" (1970, p. 92). His approach is completely consistent with a cladistics view of science. Normal science would represent the current occupants of the science clade while defunct scientific theories would represent extinct branches. This view of a science, as being made up of a number of current and extinct branches, is consistent with the approach of this study.

In fact, Kuhn's approach extends the evolutionary argument by tying it to the more modern evolutionary theory of punctuated equilibrium: the idea that evolution proceeds unevenly over the course of time. It has been shown in biological evolution that there are long periods of small incremental changes punctuated with short periods of very rapid change. In an analogous manner, normal science would be seen as that science which is practiced between periods of rapid evolutionary change. The periods of rapid evolution would be designated as revolutionary science.

This is also consistent with the process that Kuhn describes as occurring when normal science has been confronted with an increasing numbers of anomalies: "not to renounce the paradigm that has led them into crisis" (Kuhn, 1970, p. 77); rather new paradigms are developed that are in conflict with the accepted paradigm. "The decision to reject one paradigm is always simultaneously the decision to accept another, and the judgment leading to that decision involves the comparison of both paradigms with nature *and* each other" (Kuhn, 1970, p. 77). Thus a new theory must be created and selected for survival before the old theory is rejected.

Chinn and Brewer describe that “there are seven basic responses [to anomalous data]” (1993, p. 4). Only one of these responses is to reject the currently accepted theory. They constructed a theory of conceptual change that followed from their perspective about the nature of science.

> According to Richard Muller (1988), professor of physics at the University of California at Berkeley “When presented with a new, startling, and strange result, it is easy to come up with reasons to dismiss the finding. Even if the skeptic can’t find and outright mistake, he can say, ‘I’m not convinced.’ In fact, most scientists (myself included) have found that if you dismiss out of hand all claims of great new discoveries, you will be right 95% of the time (pg. 71)”. By this standard, it appears that compared with scientists, science students may be remarkably open to new data! (Chinn & Brewer, 1993, p. 6)

In his chapter titled “A Realist View of Logic, Physics and History” (1979, pp. 285-318) Popper explores what he describes as the three main theories of truth… the correspondence theory, the coherence theory and the pragmatic usefulness theory. The correspondence theory holds that a theory must correspond with the facts; the coherence theory says that a theory must be consistent with other accepted theories; and the pragmatic usefulness theory says that a theory must be useful. These are not inconsistent goals since all three could be accomplished by a single theory that agrees with the facts, is consistent with other theories and is useful. However, the reason for the three theories is the question of limitation. Can we ever know the truth to the degree required by the correspondence theory? If not, the other two approaches may be as much as we can hope for.

While Popper goes on to reject all three theories and then embrace a modified version of the correspondence theory based on the work of Tarski, I found the argument that he cites from Tarski unconvincing. The cladistics view of science would connect with Popper's theory of truth as pragmatic usefulness. Since Popper rejects usefulness as a criterion for truth, it is worth exploring Popper's position and see how my position differs from his.

> Although I am an opponent of pragmatism as a philosophy of science, I gladly admit that pragmatism has emphasized something very important: the question whether a theory has some application, whether it has, for example, predictive power. Praxis…is invaluable for the theoretician as a bridle: it is a spur because it suggests new problems to us, and it is a bridle because it may bring us down to earth and to reality if we get lost in over-abstract theoretical flights of our imagination. All this is to be admitted. And yet, it is clear that the pragmatist position will be superceded by a realist position if we can meaningfully say that a statement, or a theory, may or may not correspond to the facts. (Popper, 1979, pp. 311-312)

My embrace of usefulness is based on my belief in the evolutionary nature of science as a clade of mental tools and the vital role of usefulness in driving that evolution. If correspondence to reality were provable, so much the better: but due to the fundamental limitations of our perceptions and cognition, we do not have access to ultimate Truth. "'Seeing things' in the world – gaining information about them is a complex cognitive accomplishment….observation is theoretically based, as well as empirical. The notion of pure and indubitable 'data' is no longer regarded as a serious possibility in the philosophy of science, nor is it commonly used in the avowed warrants of professional science" (diSessa & Sherin, 1998, p. 15).

Further, usefulness in its broadest sense is quite a lot as long as, under the term usefulness, one includes that set of theories that make mental tools useful with respect to one another. Thus the entire structure of scientific and mathematical thought can be useful, if only in that it makes further work in mathematics and science possible. This is the definition of usefulness that drives the natural selection process described above and that has allowed us to develop the rich sets of mental tools, known as science and mathematics that underlie this study.

An important implication of this perspective towards science is that what we teach our students must be shown to be useful: usefulness drives tool development, construction and evolution: useless tools are not selected for learning. Recognizing that science is a set of tools makes it clear that that same condition applies to science instruction. However, usefulness should not be confused with the idea of everyday "relevance". A tool can be considered useful if it allows students to solve problems with which they are confronted in a school environment. As long as problems are rich and interesting, tools that help solve them will seem useful. This reinforces the importance of problem solving as a pedagogical approach.

Mathematics and Physics as Clades of Mediational Tools

Both mathematics and science represent high-level mental mediational tools. As is the case with all such tools, they mediate both between man and the world as well as between other mediational tools, including each other. While they were initially developed in the context of the world, they gained much greater power when they become decontextualized and applied to not only the world but to enhancing the power of other tools. The synergy of combining the use of mediational tools to augment each other is a key factor in man's rapid sociocultural evolution. Both science and mathematics represents dramatic examples of that. In fact, that is a key reason why all governments in the world make achievement in mathematics and science education such high priorities.

Lakoff and Nunez (2000) make the argument, though not all mathematicians would agree, that mathematics is a direct consequence of our physical bodies and the neural connections within our minds. No matter how abstract a mathematical concept may seem; that concept can be traced back to our physical bodies, our sensory perceptions and the cognitive structure of our brains. The abstraction and decontextualization of those concepts is done through the use and blending of metaphors that relate back to our most primitive understandings. They refer to this as "embodied mathematics".

They argue that "to understand a mathematical symbol is to associate it with a concept – something meaningful in human cognition that is ultimately grounded in experience and created via neural mechanisms" (Lakoff & Nunez, 2000, p. 49). Furthermore, they state that, "our linear, positional, polynomial-based notational system is an optimal solution to the constraints placed on us by our bodies (our arms and our gaze), our cognitive limitations (visual perception and attention, memory, parsing ability), and possibilities given by conceptual metaphor" (2000, p. 86).

This approach towards mathematics radically lowers the barrier between physics and mathematics and may explain why they are so inextricably intertwined. It is hard to find a clear difference between mathematics and physics if both are rooted in our bodies, senses and minds. In fact, many of the arguments made by Lakoff and Nunez relate to space, time, distance, velocity, etc. and are every bit as applicable to physics as they are to mathematics.

Phenomenological primitives (p-prims) represent the pieces of the "knowledge in pieces" theory outlined by diSessa (1993) to explain our intuitive understanding of the physical world. They are the schemata that exist within human consciousness that allow us to simplify our perceptions of the world into understandable patterns: "…p-prims become the intuitive equivalent of physical laws; they may explain other phenomena, but they are not themselves explained within the knowledge system". They are the "primitive elements of cognitive mechanism….that are activated in appropriate circumstances, and, in turn, they should help activate other elements according to the contexts they specify" (diSessa, 1993, p. 112).

One example of a p-prim is “continuous push”: the intuitive belief that a continuous push is required to keep an object moving at constant speed; for instance in “continuously pushing a cup across a table” (diSessa, 1993, p. 131). This is self-evident in our everyday experiences and reflects our physical intuition: if we cease pushing something it comes to a stop. Newtonian physics views this as incorrect: objects that have a constant velocity maintain that velocity unless a net force acts upon them. But we evolved in a world where there are always forces present to bring objects to a stop: usually friction. So this p-prim evolved within us, along with a long list of others, and helped us survive: they are hard for a student to give up: they are a part of their cognitive structure. In fact, these p-prims will be shown below to provide the foundation upon which we can base student learning of physics.

Sherin also argued that mathematics and physics are inextricably intertwined. “Mathematical expressions are part of the very language of physics” (2001, p. 480). “My basic argument is that, at least in some cases, the students built equations from a sense of what they wanted the equations to express” (Sherin, 2001, p. 481). “…successful students learn to understand what equations say in a fundamental sense; they have a feel for expressions, and this understanding guides their work…. We do students a disservice by treating conceptual understanding as separate from the use of mathematical notations” (Sherin, 2001, p. 482) and finally “…naïve physics knowledge provides part of the conceptual basis in terms of which equations are understood” (Sherin, 2001, p. 483).

Sherin then created a structure of "symbolic forms" which act as mathematical analogues of diSessa's p-prims. Each form represents a basic mathematical concept. Mathematical understanding is then constructed by using a combination of forms. This would then indicate that the mind has an inventory of these forms to call upon in creating mathematical understanding.

Marrongelle (2004) linked together the work of diSessa and Sherin to that of Wittmann in framing her study. She linked together their theories of knowledge in mathematics, physics and problem solving; revealing shared elements that might indicate a common foundation. "Wittmann found that students alter or revise their physical understanding to fit their misinterpretations of mathematics, or vice versa, in his study of students' understanding of waves" (Marrongelle, 2004, p. 259).

Kieran (1992) described mathematics as consisting of two forms: procedural and structural. Procedural mathematics is a lower level tool that mediates between Man and the world; allows us to make measurements and calculations about the world; and allows us to solve practical problems. It is the mathematics that lets us calculate how much carpeting we need to cover a particular floor or how many eggs are in five dozen. It is a very practical tool that has had a huge impact on man's progress.

Structural mathematics has been decontextualized from any specific problem, as well as the world. It mediates between other mental mediational tools and does not attempt to connect to the world. The concept of "functions" mediates between a range of mathematical and scientific concepts, but does not directly connect to the world. A key part of mathematics education is taking the procedural mathematics that students learn in earlier grades and decontextualizing it into a structural form.

> Their earlier work with simple formulas, such as P = 4 x S for the perimeter of a square [procedural mathematics], also provides a basis for understanding functions [structural mathematics] in their algebra classes. Furthermore, functions are taught in science classes too – but as dependency relations between variables. (Kieran, 1992, p. 409)

Kieran's approach is consistent with that of Lakoff and Nunez in that she views procedural math as being directly tied to our perception of the world and structural math as being built on that foundation. This is equivalent to viewing structural math as being the result of a metaphorical extension of procedural math.

Hiebert and Lefevre (1986) take a slightly different path to arrive at similar conclusions. They also divide mathematics into two categories: "procedural" and "conceptual". They further divide procedural mathematics into two parts: "formal language or symbol representation systems….and algorithms, or rules, for completing mathematical tasks" (Hiebert & Lefevre, 1986, p. 6). They see conceptual knowledge as being "rich in relationships….a connected web of knowledge, a network in which the linking relationships are as prominent as the discrete pieces of information (Hiebert & Lefevre, 1986, pp. 3-4). This definition of conceptual knowledge makes explicit its role as a mediating tool: this is very consistent with Kieran as well as Lakoff and Nunez.

In this view, the symbols and algorithms of procedural mathematics are mental mediational tools that can work on their own or together; but they are much more effective if they themselves are mediated: conceptual knowledge plays that role. Conceptual knowledge mediates between the individual and the world by mediating the use of other mediational tools, such as procedural knowledge. This is why it is so difficult to assess conceptual mathematics: it always works in conjunction with procedural mathematics, never alone, so its effect is difficult to isolate.

> A persistent problem is that conceptual knowledge is difficult to measure directly, and it is often inferred through the observation of particular procedures for which it is assumed prerequisite. The issue of what performance should be taken as evidence of a child having acquired a particular piece of conceptual knowledge is difficult to resolve…
> (Carpenter, 1986, p. 121)

A classic example of the extension of procedural mathematics to conceptual (or structural) mathematics through the use of metaphor can be seen in the development of geometry. Geometry was initially developed in Egypt to address the real-world problem of determining the boundaries of property after the flooding of the Nile had wiped away landmarks. The term itself means “Earth measure” and was clearly grounded in the world.

The ancient Greeks took Egyptian geometry and decontextualized it by having it speak about itself, not about the world. Through the use of idealizations for points, lines, etc. geometry transcended the world and became a tool that was able to mediate between other mental tools. Instead of mediating between man and the land, geometry began mediating between ideas. This was certainly evident by the time that Plato indicated, at the entrance to his Academy, "Let none who are ignorant about geometry enter here". Plato's Academy was not there to make take measure of the land, but rather, to take the measure of ideas. Geometry had become a tool that mediated between ideas, other high level mediational tools, not between man and the world.

Since then, mathematics has continued in the critical role of mediating between high-level mental tools. Galileo, while not the first, very famously used mathematics as a tool to develop his scientific ideas. Many of his important experiments used both procedural and conceptual mathematics in a way that established modern science. The mathematics of kinematics, while originally based on real-world observations was decontextualized and developed independently of the world. It is no more or less tied to observation than is geometry itself. In fact, the method that Oresme (circa 1320-1382) used to develop the key kinematics equations anticipated the work of Galileo by centuries and was a direct application of geometry without any recourse to experiment. "Oresme…has attracted the attention of historians of science because of his ideas on kinematics and astronomy, which anticipated to some extent those developed by Galileo in the seventeenth century" (Holton & Brush, 2001, p. 72).

Every physics course begins by establishing this foundation, a foundation that is a mathematical idealization: no observations or experiments are called for or would even make sense without first establishing it. That foundation can be as basic as conventions regarding measurements of space or time or involve more complicated relationships between those two concepts in the form of displacement, velocity and acceleration. But some theoretical foundation must exist in order for observation and experiment to have meaning.

A commonly agreed set of assumptions about the world must be in place before it is possible to even observe, or make measurements about, a ball rolling down a plank of wood and reach a scientific conclusion. “I believe that theory – at least some rudimentary theory or expectation – always comes first; that it always precedes observation; and that the fundamental role of observation and experimental tests is to show that some of our theories are false, and so to stimulate us to produce better ones. Accordingly I assert that we do not start from observations but always from problems – either from practical problems or from *a theory that has run into difficulties*” (Popper, 1979, p. 258).

Modern science, as we think of it, could only begin when the mediational tool of mathematics was combined with the scientific processes of theorizing, experimenting and observing. But mediation is a two way street. Just as mathematics serves as a mediational tool in science, bringing greater meaning to science, science serves to bring meaning to mathematics. There are an infinite number of possible mathematical systems. They are developed in a manner that makes them self-consistent, but not necessarily useful outside of the domain of mathematics itself. That tool chest of mathematical systems is constantly being filled with new ideas. But until a mathematical tool has proven useful, it represents a sidebar in human sociocultural history, a practical dead-end. Once

Galileo's experiments proved the usefulness of the seeds planted by Oresme, that had lain dormant for hundreds of years, they could sprout. With that usefulness firmly established, that branch of mathematics was selected to flourish.

As is true of all mediational tools, they only become selected for survival when they have proven useful. Useless tools are discarded while useful tools form clades that flourish. All the branches of mathematics associated with the successful experiments of Galileo grew in importance and that entire mathematical perspective was incorporated into our culture. Thus, mathematics mediated the advent of modern science, which led to science mediating the advance of mathematics.

Just as ontogeny recapitulates phylogeny on a biological level, the same is true on the level of mediational tools. A student must first learn the mediational tool of mathematics in order to explore physics. However, the application of that tool to physics gives that mathematics new meaning. Through its application to solving problems that mathematics is shown to be useful. Once found meaningful and useful, human nature leads the student to practice the use of that tool until it is mastered. A physics course that promotes the use of mathematical tools to solve rich and interesting problems will promote the learning of both physics and mathematics.

Science and mathematics education

Students learn the mediational tools of science and mathematics in a school environment. These tools are distinct from the everyday understandings that emerge from an unorganized interaction with the world. As Popper puts it, "…there seems to be a commonsense theory of knowledge: it is the mistaken theory that we acquire knowledge about the world by opening our eyes and looking at it, or, more generally, by observation" (Popper, 1979, p. 34).

This separation from the everyday experience of the world is what makes these subjects so important in learning a theoretical approach towards problem solving. Science education must encourage students to understand that "science is the domain of inquiry that goes beyond what our senses tell" (Duschl, Gedeon, Ellenbogen, & Holton, 1999, p. 530). An important aspect of this is to help students understand the transition from "…sense perception observation to theory-driven observation…to cross the boundary from phenomenal common sense explanations to theory-driven scientific explanations" (Duschl, Gedeon, Ellenbogen, & Holton, 1999, p. 525).

Hestenes et al. point out the need to build scientific understandings on the foundation of everyday thought (Hestenes, Wells, & Swackhamer, 1992). "Every student begins physics with a well-established system of common-sense beliefs about how the physical world works derived from years of personal experience….These beliefs play a dominant role in introductory physics" (Hestenes, Wells, & Swackhamer, 1992, p. 141). As a result, physics education must build upon the knowledge that resides within the student when they enter the class, not battle with it. "The commonsense alternatives to the Newtonian concepts are commonly labeled misconceptions. They should nonetheless be accorded the same respect we give to scientific concepts. The most significant commonsense beliefs have been firmly held by some of the greatest intellectuals of the past, including Galileo and Newton" (Hestenes, Wells, & Swackhamer, 1992, p. 142).

How students intuitions can be used to teach them physics can be illustrated with a specific example. In the section above, I discussed the notion of a "continuous push": the intuitive belief that a continuous push is required to keep an object moving at constant speed: for instance in "continuously pushing a cup across a table" (diSessa, 1993, p. 131). Newtonian physics views this as incorrect: objects that have a constant velocity maintain that velocity unless a net force acts upon them.

Long efforts to overcome p-prims and convince students that they are "wrong" are usually met with frustration as rational explanations only hold within the context in which they are made: in a new context the student reverts to their p-prim. This has been consistently found by the use of the Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992). While heroic efforts have resulted in some progress in this measure, it must be recognized that there are equivalent p-prims guiding our intuition in a wide range of subjects: energy; thermodynamics; optics; fluids; magnetism; electricity; etc. A lifetime could be spent developing "Inventories" for each of these and battling with students to lay down their p-prims.

A more positive approach is to employ those p-prims as teaching tools and use them to solve problems. While they will undoubtedly persist, overcoming them is not the goal of science education: we are aiming to develop the analytical thinking and problem solving skills of our students so that they can think beyond their intuitions, not refute them.

So, in this case, I would first develop the Newtonian framework wherein if no net force acts on an object it will maintain its velocity; then I would push an object and have it come to a stop when I stop pushing it; I would then ask the students to talk to each other to reconcile this apparent conflict. They will themselves invent the force of friction in order to reconcile the two frameworks: their p-prims and the Newtonian theory.

Without p-prims teaching physics would be impossible: we rely on students to understand the meaning of works like force; push; balance; light; dark; heavy; hot; cold; etc. Without p-prims we would have no way to even begin talking about the world. The same is true of mathematics: without physical intuition we would lack the words to speak of physics or mathematics.

It is useful to consider those commonsense beliefs as being limited to certain contexts: the Newtonian framework subsumes those commonsense approaches in the same manner that Einstein's General Relativity subsumes Newtonian gravity. Each more general theory does not so much prove its predecessor wrong so much as prove itself more useful in a new context. As Hammer states, "From the misconceptions perspective, students are not simply ignorant: They have knowledge about the physical world; their knowledge is reasonable and useful to them; and they use that knowledge to understand what they hear and see" (1995, p. 1319).

As we educate students we need to incorporate their everyday beliefs into a larger framework, not fight against them. As diSessa put it, "…the development of scientific knowledge is possible only through reorganized intuitive knowledge" (diSessa, 1993, p. 108). Those everyday beliefs are never fully replaced as they are still more useful in certain contexts than the more general theories. Newtonian theory is still used to calculate the orbits of the Global Positioning Satellites but is useless in keeping their clocks synchronized. Also, it is a lot easier to say that we will begin our hike at sunrise than when the rotation of the earth brings the sun above the horizon. In fact, the system of celestial navigation used by ocean going vessels continues to use the Ptolemaic model of the earth being stationary: it is simply more useful, for that application, than the Copernican theory.

Choosing between paradigms is a theme throughout modern physics. Thorne (1994), the Feynman Professor of Physics at Caltech, points out that he uses whichever paradigm works best for a particular problem. The question of underlying reality is unimportant to him: the only question is usefulness. He speaks of how "theoretical physicists, as they mature, build up insight into which paradigm will be best for which situation, and they learn to flip their minds back and forth from one paradigm to the other, as needed…They may regard spacetime as curved on Sunday, when thinking about black holes, and as flat on Monday, when thinking about gravity waves. This mind-flip is similar to that which one experiences when looking at a drawing by M. C. Escher" (Thorne, 1994, p. 403).

Tao and Gunstone (1999) found that students also use different explanations in different contexts and for different purposes. They cite Linder in making the argument that students use different conceptual models to explain phenomena in different contexts and that this is the same as what scientists do. They found in their study that "[students] vacillated between alternative and scientific conceptions from one context to another. The vacillation shows that students accepted the scientific conceptions in some contexts but were unwilling to give up their alternative conceptions in other contexts….In some contexts students find the scientific conception intelligible, plausible, and perhaps also fruitful, but in another context they find it intelligible, but not plausible, and therefore reject it" (Tao & Gunstone, 1999, p. 877). Asking whether a concept is fruitful in a given context is the same as asking if it is useful.

Wertsch explains that Vygotsky felt that the difference between scientific and everyday concepts is that scientific concepts fit into an overall system while everyday concepts do not. "[The] first and most decisive distinction between spontaneous and nonspontaneous, especially scientific, concepts is the absence of a system in the former' (1934a, p. 194)" (Wertsch, 1985, pp. 102-103). Importantly, this allows scientific concepts to deal with other concepts and not just with the objects being observed. "In the case of spontaneous concepts, the child's attention is 'always centered on the object being represented and not on the act of thought that grasps it' (ibid.). In contrast, 'scientific concepts, with their quite different relations to an object, are mediated through other concepts with their internal, hierarchical system of interrelationships' (ibid.)" (Wertsch, 1985, pp. 102-103).

Scientific concepts are also unique in that, while being theory-driven, they must also meet the criteria of being testable. Just because an idea seems reasonable and is consistent with previous beliefs does not make it scientific. "When Kant said that our intellect imposes its laws upon nature, he was right – except that he did not notice how often our intellect fails in the attempt: the regularities we try to impose are *psychologically a priori*, but there is not the slightest reason to think that they are *a priori valid*, as Kant thought" (Popper, 1979, p. 24).

Chinn and Brewer (1993) point out that students come to school not only with a commonsense understanding about the world but also a set of epistemological beliefs about science. "There is evidence that even the youngest elementary school students are guided by a sound 'commonsense' epistemology (see Conant, 1951)" and "children come to school already equipped with some of the criteria for judging among scientific theories, criteria have been proposed by such philosophers of science such as T. Kuhn (1977) and Laudan (1977) as rational criteria for making choices among scientific theories" (Chinn & Brewer, 1993, p. 16). These epistemological beliefs must be recognized by instructors as they form a foundation for future learning.

Decontextualization is fundamental to the cladistics view of science and mathematics. As in the development of each mediational tool, the process of developing a new tool begins with concrete experience and interaction with the world. However, as a mental tool is refined it separates from the original context in which it was developed and takes on its own meaning and usefulness which can be applied to other contexts and with respect to other tools. Wertsch points out that science and mathematics must be understood in that sense as being separate from their initial contexts.

> [Vygotsky] argued that the forms of counting observed in primitives is heavily dependent on the context; that is, counting relies on the perception of concrete objects and settings…. In calculation, decontextualization is tied to the emergence of a number system in which a quantity can be represented independently of any concrete perceptual context. Indeed quantity can become an abstract object itself instead of a meaning tied to a set of concrete objects. With decontextualization, it becomes possible to talk about two or three without specifying two or three *what*. Systematization makes it possible to account for the meaning of mathematical signs without relying on the context to their use or application. Thus two can be defined within the number system as one plus one, three minus one, four minus two, and so on. (Wertsch, 1985, p. 33)

This separation of general scientific or mathematical concepts from the specific context in which they were first developed was one of the specific values that Vygotsky saw in the learning of science. The separation of the subject from its context leads the student to make deliberate use of a higher degree of theoretical thinking, to be able to generalize from specific cases to general principles. This theoretical approach could then be applied to developing a problem solving approach that would have more general value.

Hiebert and Lefevre (1986) described this same sort of layered process of learning when they spoke of how students first learn procedural knowledge, which then leads to the learning of conceptual knowledge. More specifically, they described how procedural and conceptual knowledge naturally develop in tandem before students enter school and how these two forms of knowledge often became separated in the school environment where procedural knowledge is not used, as it should be, to form the basis of conceptual knowledge. “Although it is possible to consider procedures without concepts, it is not easy to imagine conceptual knowledge that is not linked to some procedures” (Hiebert & Lefevre, 1986, p. 9). However, for procedural knowledge to be effectively employed it must be mediated by conceptual knowledge. The medication of procedural knowledge by conceptual knowledge can: “(a) enhance problem representations and simplify procedural demands; (b) monitor procedure selection and execution: and (c) promote transfer and reduce the number of procedures required” (Hiebert & Lefevre, 1986, p. 11).

> For Vygotsky scientific concepts are characterized by a high degree of generality and their relationship to objects is mediated through other concepts. By the use of ‘scientific concept’ Vygotsky referred to concepts introduced by a teacher in school, and spontaneous concepts were those that were acquired by the child outside contexts in which explicit instruction was in place. Scientific concepts were described as those

> which form a coherent, logical hierarchical system. According to Vygotsky (1987) children can make deliberate use of scientific concepts, they are consciously aware of them and can reflect upon them. (Daniels, 2001, p. 50)

Vygotsky viewed the development of a theoretical approach to the world as a key value of formal education in general and scientific education specifically. This is accomplished by the development of testable theories that explain the world. As Bruner describes it, "What is unique about us as a species is that we not only adapt to the natural and social worlds through appropriate actions, but we also create theories and stories to help us *understand* and *explain* the world and our actions in it" (1997, p. 64). We then connect these stories about the world into a structure where these stories relate to each other.

> The dependence of scientific concepts on spontaneous concepts and their influence upon them stems from the unique relationship that exists between the scientific concept and its object…this relationship is characterized by the fact that it is *mediated through other concepts*. *Consequently, in its relationship to the object, the scientific concept includes a relationship to another concept*, that is it includes the most basic element of a concept system. (Vygotsky, 1987b, p. 192)

This can be seen specifically in the relationship between arithmetic and algebra.

> We found an analogous relation between old and new formations in the development of concepts of arithmetic and algebra. The rise from

> preconcepts (which the schoolchild's concept of arithmetic usually are) to true concepts, such as the algebraic concepts of adolescents, is achieved by generalizing the generalizations of the earlier level. At the earlier stage certain aspects of objects had been abstracted and generalized into ideas of numbers. Algebraic concepts represent abstractions and generalizations of certain aspects of numbers, not objects, and thus signify a new departure – a new, higher plane of thought. (Vygotsky, 1986, p. 202)

> Learning a foreign language raises the level of the child's native speech in much the same what that learning algebra raises the level of his arithmetic thinking. By learning algebra, the child comes to understand arithmetic operations as particular instantiations of algebraic operations. This give the child a freer, more abstract and generalized view of his operations with concrete quantities. Just as algebra frees the child's thought from the grasp of concrete numerical relations and raises it to the level of more abstract thought, learning a foreign language frees the child's verbal thought from the grasp of concrete linguistic forms and phenomena. (Vygotsky, 1987b, p. 180)

The everyday understandings that each student brings with them to the classroom are correct within their context. It is not the role of science education to confront those beliefs and try to prove them wrong. Science education must show students how their prior beliefs and understandings are particular outcomes of more general principals. At the same time, it must show the usefulness of learning the more general principles. After all, Man has survived with those "mistaken" beliefs for millennia, so they must be effective in their context: why construct new understandings that contradict those beliefs.

Confronting students' prior beliefs leads, at best, to piecemeal acceptance and understanding. On the other hand, teaching them the theoretical style of thinking that allows them to understand both the new scientific principle and see how it subsumes their prior understanding accomplishes two things: it helps them learn the new principle as well as a theoretical/analytical style of thinking. However, no matter how well they are taught, students should not be expected to discard their prior understandings in a few years of instruction. Committed scientists make serious, but only partial progress, towards that goal within their own fields over the course of their lifetime. A more reasonable outcome for mathematics and science education is the adoption of the thinking strategies that are their hallmark.

Problem Solving: A Key Objective of Science and Mathematics Education

The coordinated instruction of physics and algebra serves to expose students to physics applications of algebra concepts while those concepts are being learned in algebra. This application increases students' drive to learn algebra, in particular, and mathematics, in general, by showing its usefulness, an important aspect of motivation. "Some of the most widely decried failures of transfer - failure to apply knowledge learned in school to practical problems encountered in everyday life - may largely reflect that material taught in school is often disconnected from any clear goal (Gick & Holyoak, 1987, p. 131)"

(Butterfield, Slocum, & Nelson, 1993, p. 232). While the goal of being able to solve physics problems is itself confined to the school environment, it reflects a task that requires algebra, and thereby represents a benefit of learning algebra. Further to that point, "…freshman who enjoy physics often see that math will help them understand it better, getting them excited about math as well as science" (Pasero, 2003, p. 15).

Also, the physics course provides an increase in the number of algebra problems each student encounters.

> Given more examples, students can form a frame (or script or schema) or a set of discriminative stimuli that make an appropriate response more likely for subsequent problems. Viewing choice of solution to later problems as a matter of analogical reasoning, we can say that more examples allow structural features and goals to affect access to a learned solution and to guide appropriate mapping onto later problems (Carbonell, 1986; Holyoak, 1985).
>
> (Butterfield, Slocum, & Nelson, 1993, p. 219)

Therefore, the physics course should improve the mathematical understanding being developed in the algebra class. Beyond that, both the algebra and physics courses should build general problem solving skills. These skills represent a crucial goal of the study of physics and mathematics.

Subjects taught in school are presumed to benefit the student beyond the specific material taught in a particular class. This is certainly the case for physics. Very few college students in a physics course are physics majors.

Even among those who graduate as physics majors, most report that the content taught in their physics classes was the least important knowledge they gained.

In his 1999 Millikan lecture, Alan Van Heuvelen (2001) cited a survey, conducted by the American Institute of Physics, among students who had received degrees in physics and were in the workplace. Respondents were asked to rank ten skills that they had learned in their study of physics in the order of importance that they played in their occupation. It was found that “physics knowledge was the least used ‘skill’ reported in this list” (Van Heuvelen, 2001, p. 264). The top skill that they indicated learning from their physics courses was “problem solving”.

McDermott speaks to the problem of the mismatch between instructor and students in a typical college introductory physics course due to the fact that only 1 in 30 of the students in the class is a physics major and instructors tend to think of their students as being “very much like themselves” (McDermott, 1991, p. 302). This would be even more of an issue in a high school physics class and emphasizes the need to teach to a more general goal, such as problem solving, rather than with the goal of turning students into physicists. For instance, “Scardamalia and Bereiter (1991, 1996) suggest that the kind of education that will best prepare students for life in a knowledge society should foster: flexibility; creativity; problem-solving ability; technological literacy; information-finding skills; and a lifelong readiness to learn” (Daniels, 2001, p. 103).

Reif supports this when he states that, “students will have to function in a complex and rapidly changing technological world where they will profit little from knowledge that is rotely memorized or poorly understood" (1995, p. 17). He goes on to say that "one should try to analyze the thought processes required for effective problem solving, and that one should then try to teach explicitly a problem-solving method based on this analysis" (Reif, 1995, p. 27).

For high school students this argument is even stronger since very few go on to become science or mathematics majors. Therefore, the teaching of physics must have value outside the realm of physics knowledge itself. It must reside in something much more general, such as "problem solving." "Wells (1994a) further suggested that the learning of school knowledge, and specifically the development of scientific concepts, tends to be treated as an end in itself. He proposes rather it should be understood as the appropriation and further development of a set of tools that is used for problem solving in the achievement of goals that the students find personally significant" (Daniels, 2001, p. 101).

Hammer et al. concluded that instruction in how to solve specific problems (sequestered problem solving or SPS) and instruction aimed at solving unknown future problems (preparation for future learning or PFL) might differ. They stated that, if confirmed, this would have "implications that are profound, for both instruction and assessment". Specifically, this would mean that the "effort that has gone into developing instructional materials that help students overcome common misconceptions, as measured by standardized assessments such as the Force Concept Inventory…., we might be shortchanging our students in the long run" (Hammer, Elby, Scherr, & Redish, 2000, p. 23).

The same is true for mathematics. The mathematics taught to students in high school is for the most part applicable only in later mathematics and science classes. It is the rare individual who solves trigonometric equations, or even algebraic equations, in daily life. Therefore, the goal of problem solving has emerged as a prime focus of mathematics education. As Schoenfeld (1992) states, "problem solving has, as predicted in the 1980 *Yearbook of the National Council of Teachers of Mathematics* (Krulik, 1980, p. xiv) been the theme of the 1980s" (pp. 334-335).

Physics and mathematics share the common goal of teaching students to become good "problem-solvers". As Alan Van Heuvelen put it, "One objective of our instruction is to help students learn to (1) construct qualitative representations of physical processes and problems, (2) reason about the processes using these qualitative representations, (3) construct mathematical representations with the help of the qualitative representation, and (4) solve the problem quantitatively. Students are learning to think like physicists" (Van Heuvelen, 1991, p. 892). Similarly, Schoenfeld (1992) said that an important goal of mathematics instruction is to "help students to develop a "mathematical point of view" – a predilection to analyze and understand, to perceive structure and structural relationships, to see how things fit together. (Note that those connections can either be pure or applied.) It should help students develop their analytical skills, and the ability to reason in extended chains of argument" (p. 345).

Van Heuvelen and Schoenfeld described similar outcomes for the successful student. Each valued their field for the reasoning and problem solving skills it builds in those that study it. With such similar goals, it seems reasonable that mathematics and physics should prove to be complementary disciplines.

In Heller et al.'s work on developing problem solving skills in physics through group work it was noted that "the basic form of the five-step strategy designed for our students was strongly influenced by the work of Frederick Reif and Joan Heller, but it has many elements in common with Alan Schoenfeld's framework for mathematics problem solving" (Heller, Keith, & Anderson, 1992, p. 628). The authors of this study recognized that the problem solving approaches of mathematics and physics are deeply related.

An important part of problem solving is the ability to generate mental models that can be used to envision and compare alternative solutions. In 1994, Redish decried typical physics classes for their failure to develop the skills needed to develop those models, "…as physics teachers we fail to make an impact on the way a majority of our students think about the world" (p. 796). In his 1998 Millikan lecture, Redish (1999) expanded on this, stating, "physics is really about building mental maps that allow us to make sense of the world. To do this we have to create map structures that match not only what happens in the physical world but the ways we can comfortably think about it" (p. 570).

Teaching physics and mathematics must develop in students the ability to solve both simple concrete problems as well as complex open ended problems. The former are similar to the highly structured problems found at the end of most mathematics and physics textbooks. People confront a number of these straightforward problems every day so the value in learning how to solve them should not be ignored. In fact, a good percentage of one's life is spent dealing with concrete low level problems. Some examples include which cereal box size offers the best value, how many widgets to place on your next reorder or how much of a tip to leave on your lunch bill. This sort of exercise is like the low level problems found in an algebra or physics book. They come in a lot of forms and confront people every day.

But people also encounter complex multi-step problems. As problems become more complex their solution requires the construction of a mental map describing the problem and allowing the playing out of alternative solutions. Thus deciding whether to buy a home or rent an apartment raises questions of cash flow, marital plans, job satisfaction, job stability, analysis of the cost of buying versus renting, projections about the future real estate market, etc. A myriad of factors must be identified and played out against each other in order to arrive at a solution. Addressing this sort of open ended problem is much more complex than the most ambitious problems at the end of a chapter of a standard mathematics or physics textbook. However, the required problem solving skills are not fundamentally different from those learned in solving the more complex multi-step problems that should be part of a physics or mathematics curriculum.

Problem solving is both an educational goal and an educational technique. The mediational tools that are employed are all supported in the process of solving a problem: they are given meaning, shown to be useful and are practiced.

Thus problem solving is a means of helping students construct the mediational tools that are employed. However, problem solving is also a highly regarded outcome in its own right. The ability to think analytically and work through complex problems is highly valued by both individuals and society.

Problem solving in mathematics and physics allows the development of those skills in a simpler context than is available in everyday life. But developing those skills and then using them to solve problems in multiple settings requires that transfer take place between domains.

Transfer and Mental Models

"Transfer cannot be distinguished from learning. Teaching and learning are a tapestry that does not lend itself to such labels as near transfer and far transfer" (Butterfield, Slocum, & Nelson, 1993, p. 219). If education in general, and science or mathematics education in particular, is to have more applicability and value than teaching students to solve specific textbook problems in a specific classroom on a specific day, transfer is critical. Otherwise, the goal of imparting the skills to solve a range of problems in a variety of domains cannot be achieved.

The question of whether transfer occurs is hotly debated. However, issues of definition obscure much of this debate. Detterman (1996) explained that "transfer" can refer to near or far transfer, involve specific or general content and be affected by deep or surface structure. This would lead to the conclusion that the question of whether transfer is likely to occur cannot be answered without precisely specifying the type of transfer. Instead, he concluded that, "we generally do what we have learned to do and no more. The lesson learned from studies of transfer is that if you want people to learn something, teach it to them. Don't teach them something else and expect them to figure out what you really want them to do" (p. 21). This extreme position could be interpreted to mean that being taught to drive one car would not help in driving another one. Of course, that does not make sense. This position violates common sense and is not supported by the literature.

Gick and Holyoak (1980) conducted a pivotal series of experiments aimed at answering the questions, "Where do new ideas come from? What psychological mechanisms underlie creative insight" (p. 306)? The generation of new ideas through inter-domain analogical thinking would have to be considered far transfer. They used Duncker's (1945) radiation problem as their test problem and used a range of varyingly analogous problems for training.

In Duncker's radiation problem, a patient has an inoperable stomach tumor. Certain rays with sufficient intensity can destroy organic tissue. How can those rays be used to destroy the tumor without also destroying the healthy tissue surrounding it? The correct solution is to direct the rays at the tumor from a number of different directions so the tumor receives a fatal dose while the healthy tissue does not. Without any training, with analogous problems, only 10% of subjects arrived at this solution.

Far better results were achieved by students who had been taught how to solve an isomorphic problem. The more isomorphic the training problem, the more likely it was to be used to find the correct solution to the radiation problem.

Being told that the training problem would be helpful increased its successful use. The most analogous story involved a general who wanted to capture a fortress. A system of roads led to the fortress like spokes on a wheel. However, he could only send a small army down any one road. The solution was to send many small forces down each road so that they converged at the fortress.

In the first experiment, subjects were told that the analogous story would help to solve the radiation problem and the results dramatically demonstrated transfer. “All 10 subjects who were given the Attack-Dispersion story produced this [correct] solution, whereas not a single control subject did so” (Gick & Holyoak, 1980, p. 320).

In a later experiment, subjects were first asked to solve the radiation problem without being given the hint that the analogous story could help. About 20% solved the problem (Gick & Holyoak, 1980, p. 342). After being given a hint to use the training story that rose to 75%. This compares to only 10% of those given no analogous story being able to solve the problem. Significant transfer occurred without the hint, and was dramatically enhanced by the hint. These experiments showed that inter-domain transfer could be robust.

Gick and Holyoak (1983) later extended their research to determine if there were methods of improving the spontaneous recognition of analogous solutions. They found that the use of two analogous stories, combined with having the subject summarize the principle connecting those two stories, significantly improved performance. This was most effective when a diagram was used to explain the solutions. Subjects were able to spontaneously recognize the solution to a new problem 60% of the time and, with a hint, more than 90% of the time.

This study showed that it is possible to transfer prior learning to new problems. It also showed that the best way to accomplish that is with multiple examples and multiple representations, in this case diagrams. Interestingly, an explanation, by the experimenter to the subject, of the underlying principle added very little to the ability to solve later problems.

Bassok and Holyoak (1989) found strikingly asymmetrical transfer between algebra and physics, with robust transfer from algebra to physics and almost no transfer from physics to algebra. This was attributed to characteristics of those domains and threatened the idea that physics was a productive training ground for problem solving.

However, in 1990, Bassok reversed herself on that conclusion. She recognized that while the algebra training problems in the 1989 study were isomorphic with the test problems, the physics training problems were not. The physics training problems used intensive (rate-like) quantities, such as meters per second, while the algebra training problems and the test problems used extensive quantities, such as dollars. After noting that this led to an unfair comparison, she redid the study and found that transfer from physics to other fields can be robust, a significant reversal from the conclusion of the 1989 paper. Unfortunately, the change was presented with sufficiently subtlety that references are still made to the mistaken conclusion of the 1989 study (Bassok, 1990).

I quote her at length below as the previous study (Bassok & Holyoak, 1989) has been cited extensively over the years to support a position that Bassok (1990) no longer supports.

> Kaput (1986) argues that variables denoting extensive quantities and those denoting intensive quantities may imply different interpretations of the operations that are permitted on them…. Transfer from physics could have been blocked by … by the mismatch between the intensive variable of speed and the conceptually extensive variable in the transfer problems (e.g., people, chairs)…. The present study substantially extends the results of the Bassok and Holyoak (1989) study showing that abstraction and transfer can be obtained following training in content-rich quantitative domains and are not limited to content-free algebraic training…. In Experiment 2 (intensive condition) after learning a physics chapter dealing with accelerated motion, 70% of the students spontaneously recognized that constant decrease in the formation of precipitate is like deceleration and that the total amount of precipitate can be calculated by using the distance equation introduced in the physics chapter (Bassok, 1990, pp. 531-532).

Smith and Unger (1997) discussed intensive versus extensive quantities in their literature review, indicating that “the development of proportional reasoning [involving intensive quantities] is a gradual and protracted process…extending well into adolescence and adulthood” (p. 147). This further illuminates the asymmetry of the Bassok and Holyoak (1989) study which used quantities of money or lengths (discrete and extensive) in the domain of algebra while using meters per second (continuous and intensive) in the domain of physics. "One reason that intensive and extensive quantity pairs in physics may be so difficult to distinguish is that they involve continuous quantities that cannot be directly visually apprehended (such as density and mass, temperature and heat)" (Smith & Unger, 1997, p. 147).

Smith and Unger (1997) studied transfer between problems involving three intensive quantities that varied in discreteness: dots per box, sweetness and density. The dots-per-box model was fundamentally discrete, while sweetness was made somewhat discrete by measuring it in spoonfuls of sugar. No attempt was made to create a discrete model of density.

The subjects, twenty 7^{th} grade students, best understood dots-per-box and least understood density. Smith and Unger found that some transfer occurred from dots-per-box to sweetness, but almost no transfer occurred from either of those to density. The more continuous and/or intensive the quantity, the more difficult it is for students.

They also found that "asking students to make connections between two domains that are not equivalently understood typically enhances understanding of the less well understood domain in a supportive, socially scaffolded instructional context…. Hence it is wise to ensure strong understanding of the source domain first" (Smith & Unger, 1997, p. 174). This supports the idea of inter-domain transfer and emphasizes the need for a positive open environment to facilitate that transfer. Interpersonal dialogue, symptomatic of an open environment, facilitated transfer.

Marrongelle (2004) posed the question, “how [do] students in an integrated calculus and physics class use physics to help them solve calculus problems” (p. 258). In this case study, she monitoring eight students in an integrated physics / calculus course and found that “some students introduce contexts to solve mathematics problems; this result suggests that students can use contexts in meaningful ways to solve mathematics problems, contrary to past research that has pointed out the difficulty students have solving problems in context” (Marrongelle, 2004, p. 258). “For both Rob and Brad, the derivative concept is first and foremost thought of in terms of kinematics” (Marrongelle, 2004, p. 264).

Novick (1988)studied the use of analogous stories to determine what factors affected transfer between different problems. After carefully outlining the Gick and Holyoak (1980) study, she hypothesized that while analogy was an effective means of transfer, surface features of stories prevented subjects from recognizing analogous solutions. In a series of experiments, she presented analogous stories to subjects and determined when negative and positive transfer occurred. Negative transfer is when surface features lead to false solutions between situations that appear analogous but are not, while positive transfer is when reasoning by analogy leads to correct solutions. Novick (1988) found that “substantial positive transfer was observed for experts but not for novices. Spontaneous negative transfer was observed at all levels of expertise, but was weaker for experts" (p. 518).

Novick defined expertise by the subject's score on the mathematics section of Scholastic Aptitude Test (MSAT), indicating that subjects who perform well on that mathematics test had a higher level of transfer between training and testing problems. As training in mathematics does improve performance on that test, this suggests that students can, through the study of mathematics, improve their ability to effect problem solving transfer.

Reed, Dempster and Ettinger (1985) studied the use of analogous problems for solving mathematical word problems. They conducted experiments in which some subjects were trained to solve problems that were related to the test problem while a control group worked on unrelated problems. Students who understood the reasoning behind the solution of the training problem achieved the best results. "These results demonstrate that students can use solutions of algebra word problems to solve equivalent problems if the solutions are accompanied by an explanation of why a particular equation is used" (Reed, Dempster, & Ettinger, 1985, p. 117). Importantly, subjects needed to understand the reasoning behind how to solve the training problem in order to benefit from it. Memorizing a procedure did not teach them transferable problem solving strategies. That understanding results in improved transfer supports the idea that effective instruction is critical to developing problem solving ability. If problem solving is the goal, having students memorize procedures or passively listen to lectures is a waste of time.

Kieran (1992) pointed out the challenge of establishing transfer between qualitative and quantitative understandings of mathematics as well as to science, stating that “generating equations to represent the relationships found in typical word problems is well know to be one of the major areas of difficulty for high school algebra students” (p. 403). She then highlighted the failure to make connections between structural (qualitative) mathematics, procedural (quantitative) mathematics and science. She partially attributed this to the failure to make connections between academic classes. In the following example, the qualitative understanding that is targeted is the structural concept of mathematical “function”.

> Their earlier work with simple formulas, such as P = 4 x S for the perimeter of a square [procedural mathematics], also provides a basis for understanding functions [structural mathematics] in their algebra classes. Furthermore, functions are taught in science classes too – but as dependency relations between variables. However, the teaching of functions in algebra courses does not appear to capitalize on any of this prior experience. (Kieran, 1992, p. 409)

The failure of schools to coordinate the learning happening in different classes, either vertically (year to year) or horizontally (course to course) represents lost opportunity.

Ploetzner and VanLehn used the data from a 1989 study by Chi, Bassok, Lewis, Reimann, and Glaser and used that data to create “computerized simulation models of both conceptual problem solving and quantitative problem solving" (Ploetzner & VanLehn, 1997, p. 171). They viewed conceptual and quantitative understandings of physics as distinct entities and then measured the transfer between them. They treated standard textbook training as quantitative and viewed any gains in conceptual understanding as transfer. (This approach might also be applicable to a study of transfer between procedural and structural mathematical understanding.) They found that "the degree of transfer that occurred between them [quantitative to qualitative understanding] was 41%. This is comparable to other studies of transfer from standard physics training to qualitative understanding" (Ploetzner & VanLehn, 1997, p. 175).

They also found cases where "the student not only might have learned and repeatedly applied the definition of Newton's second law as it has been explicitly presented in the instruction but also might have derived and constructed knowledge about qualitative aspects of Newton's law that have been left implicit in the instruction" (Ploetzner & VanLehn, 1997, p. 186). This would represent a case of far transfer of deep structure.

Mitchell and Miller (1995) had fifth-grade students roll balls down a ramp whose angle could be altered. The students were asked to estimate, and then create a model, for determining the relationship between ramp angles and landing sites. The researchers found that "children's conceptions of the laws of motion, introduced by Eckstein and Shemesh (1993) are extended with an emphasis placed upon the benefits to mathematics education" (Mitchell & Miller, 1995, p. 260). Concluding, "The investigations … provide fascinating opportunities for students to study a wide variety of topics in mathematics. They will begin to realize that mathematics is a tool which can be used to help them understand their environment" (p. 262). It is unfortunate that actual student reactions and conceptual gains were not noted in the article, only possible prospective gains.

A rare opportunity to study transfer in a natural, non-academic, setting arose when a consolidation at their company forced a group of aeronautical technicians, who had had three different, but related, jobs to learn the other two jobs. Each of them needed to transfer their prior knowledge into two new domains (Gott, Hall, Pokorny, Dibble, & Glaser, 1993). The authors quoted Gick and Holyoak (1987) in support of their position that this learning was a type of transfer.

> No empirical or theoretical chasm separates transfer from the general topic of learning. Rather, the consequences of prior learning can be measured for a continuum of subsequent tasks that range from those that are merely repetitions (self-transfer), to that are highly similar (near transfer), to those that are very different (far transfer). (Gott, Hall, Pokorny, Dibble, & Glaser, 1993, p. 260)

It was found that a major obstacle to transfer among these adult men was an unwillingness to ask questions and admit what they did not know. Without a sufficiently open risk-free environment the workers chose to protect their egos rather than learn.

The researchers partially overcame this by casting the learning as a competition and indicating that the top management thought that they could not do it. “To overcome the ego barriers associated with revealing one’s lack of knowledge by the act of questioning, technicians were told that the highest level management in their organization was questioning the value of the months of resident training…. We then issued what amounted to a challenge to them to show everyone…” (Gott, Hall, Pokorny, Dibble, & Glaser, 1993, p. 274). The need for motivation and a safe environment for one’s ego, to promote transfer, is illustrated by this example and the same principle probably applies to the classroom. The need for open dialogue was also clear from their description successful learners.

> All of the technicians who showed improved performance on the posttests actively interrogated the expert tutors during the Learning Phase as they constructed their own understanding of the problems. They asked more questions, and they also produced more self-explanations, often generating additional questions from their elaborations. By comparison, weaker performers tended to ask fewer questions, showed little evidence of self-explanation, and often engaged in unproductive actions and questioning tactics. (Gott, Hall, Pokorny, Dibble, & Glaser, 1993, p. 281)

Another finding from this study was that “the primary content of transfer takes the form of abstract knowledge representations…. We observed good learners access their existing mental models of equipment structure and functions…. They then used these models to guide their performance as they crafted solutions to new problems” (Gott, Hall, Pokorny, Dibble, & Glaser, 1993,

p. 286). This describes the generalized problem-solving process that is the goal of effective instruction.

Specifically, transfer has been shown to be robust in both directions between physics and mathematics. Generally, transfer is very much improved when individuals are told that what they have learned in one setting will be useful in the new setting; when problems are isomorphic with one another; when learners are motivated; and when the underlying reasoning behind the solution to the source problem is understood.

This means that transfer can be promoted in a school environment through a school's overall program design: accomplishing this involves curriculum development stressing cross curricular articulations; professional development; and a pedagogical approach that stresses reasoning. Curricula must first be developed in such a way that there are connections between what students are learning in their various classes. Then the instructors in each course must be aware of those articulations and point them out to their students so as to promote their transfer. The pedagogical approach used in each class must stress understanding as opposed to recall: transfer is enhanced if the reasoning behind solutions is understood. Finally, motivation will be enhanced by students seeing that what they have learned in once class is useful in another.

Summary

Science and mathematics education are compelling national priorities. An educational approach that advances achievement in both these areas would be of great interest to the educational community. The approach analyzed in this study attempts to accomplish that goal, in part, reversing the sequence in which the sciences are taught.

The controversy of the order in which the sciences should be taught extends back more than a century: an analysis of the science content leads to physics-chemistry-biology but the math required for the first year course has led to the reverse. There has been a tension between the mathematics content and the physics content of any proposed first year physics course. The recent evolution in the curricula of those courses is an attempt to resolve that tension: an attempt that is now proving successful.

Our goal must be to understand our perceptual and cognitive structures and use them as a foundation on which to construct an understanding of the world that transcends them. While humans are not able to change their perceptual and cognitive structures; they have been able to develop mediational tools that stand between themselves and the world in order to interact with it more effectively. We are uniquely capable of being able to improve those tools and pass them along to succeeding generations.

Our cultural heritage represents the grand total of all the tools that have been developed, improved and passed along by prior generations. They represent a key element of human progress. The medium of biological evolution is DNA: the medium of tool evolution is society. A vital role of society is to improve and pass along tools from one generation to the next. As our tools became increasingly complex institutions were developed to expedite their transmission: educational institutions.

Education plays a fundamental role in the transmission of mental tools from generation to generation. It is certainly not to be expected that any child will discover these tools; if that were possible children would have discovered them millennia ago. The cultural heritage of our mediational tools represents our rightful inheritance; an inheritance that has been improved and passed along by all who came before us. Creating the conditions by which mediational tools may be successfully passed on to the next generation is the role of education: making education central to human society.

Educational tools were developed, improved and are efficiently passed along to the next generation in a social context: they will not be discovered by students on their own without the help of a teacher; they are very ineffectively transmitted by lecture; and they are reinforced by being actively used to solve problems. Problem solving serves both as a medium in which prior tools are used, and thereby shown to be useful, and in which new tools are developed. Since usefulness is a driver of both tool construction and evolution, it is a critical element in the educational process. A rich problem solving environment, maintained by an actively involved teacher, promotes student learning.

When students are in their Zone of Proximal Development they not only enjoy solving problems; they feel the joy of growing and becoming more effective. Students in this zone can be pictured as riding a wave. If they fall behind it, because the problems are too easy, they get bored and do not progress. If they get ahead of it, if the problems are beyond the group’s ability; they get overwhelmed, become frustrated and give up. But if the problems keep the students just at the edge of their ability, it is exciting to watch how quickly they progress.

Science and mathematics are clades of mediational tools that are learned and improved upon by each succeeding generation. As is the case with all tools, they must be shown to be useful: usefulness drives tool development, construction and evolution: useless tools are not selected for learning. However, usefulness should not be confused with the idea of everyday “relevance”. A tool can be considered useful if it allows students to solve problems with which they are confronted in a school environment.

A student must first learn the mediational tool of mathematics in order to explore physics. However, the application of that tool to physics gives mathematics new meaning and shows it to be useful. Once found meaningful and useful, human nature leads the student to practice the use of that tool until it is mastered. A physics course that promotes the use of mathematical tools to solve rich and interesting problems promotes the learning of both physics and mathematics.

The everyday understandings that each student brings with them to the classroom are correct within their context. It is not the role of science education to confront those beliefs and prove them wrong. Science education must show students how their prior beliefs and understandings are particular outcomes of more general principals while showing the usefulness of those more general principles.

Problem solving is both an educational goal and an educational technique. The mediational tools that are employed in solving a problem are all supported in the process: they are given meaning, shown to be useful and are practiced. Thus problem solving is a means of helping students construct the mediational tools that are employed. However, problem solving is also a highly regarded outcome in its own right. The ability to think analytically and work through complex problems is valuable.

If tools are to be generally applied, beyond the context in which they are learned, transfer must be promoted. Transfer is very much improved when individuals are told that what they have learned in one setting will be useful in the new setting; when problems are isomorphic with one another; when the learners are motivated; and when the underlying reasoning behind the solution to the source problem is understood.

Promoting transfer should be an objective of a school's overall educational design: accomplishing this involves curriculum development stressing cross curricular articulations; professional development that stresses those connections; and a pedagogical approach that emphasizes reasoning.

Chapter 3: METHODOLOGY

The implementation of the science program under study began with the founding of the school 6 ½ years ago. Prior to the 1999/2000 academic year (AY2000) the facility housed a full time special education vocation school and a shared-time vocational school. The full time school was phased in beginning with a 9th grade class that was inducted in AY2000 and graduated in AY2003. The first year for which SAT, HSPA and AP results are available is the year that those students reached the 11th grade, AY2002. All of those data will be used in this study. In addition, the implementation of the science program will be explained in detail from the founding of the school to the present.

In my attempt to determine the effectiveness of the program, I establish two baselines for comparison. First, I compare the students in the school to those in the state with respect to their demographic characteristics as well as their scores on Scholastic Assessment Tests (SAT's). This was to determine if the students in the school were sufficiently like those across the state to allow meaningful comparisons to be made between the two groups.

Second, I compare the scores of the school's students on the math and verbal SAT's. This was to determine if their mathematical and verbal aptitudes were sufficiently similar that their achievement in mathematics and science versus English and social studies could be meaningfully compared. Since only student achievement in mathematics and science would be attributable to the program under study, differential achievement between mathematics and science versus English and social studies would increase the plausibility that the program was responsible for any difference.

I then describe the three measures I would use to determine the effectiveness of the program: student achievement on Advance Placement (AP) tests; student achievement on the state High School Proficiency Assessment (HSPA); and the participation rate in science electives. I would be making comparisons both externally, to students across the state, and internally, to the same students' achievement outside of mathematics and science. The process of how I planned to do this and the comparisons that would be made are described in this chapter.

An important aspect of this study was also to document the program so that it could be replicated at other schools. In this chapter, I describe the two basic approaches I would use to accomplish that documentation: a full description of the program in its current state, a snapshot, and a detailed explanation of the theoretical framework of the program.

The Implementation of the New Science Program

It took six years for the new science program to reach its current form. There was no single date that it was implemented; it was a gradual, uneven process. This is the reality of schools, where decisions are ideally made for the best interests of the students; not for research purposes. Understanding the results that were obtained requires having a general picture of the process by with the program was implemented.

That process began with the launching of the school as a full time vocational/technical high school in September 1999 (AY2000). The school started with about 120 students, of whom 82 went on to graduate. There was a high attrition rate in the initial years due to the difficult process involved in recruiting qualified students to a new vocational high school. Attrition rates have improved steadily and are now quite low, and usually attributable to a student's family moving to another county. The population now varies between 150 and 180 students per grade.

The new math and science sequences were originally developed for the Pre-Engineering program: one of more than a dozen programs in the school. Pre-Engineering was originally established to serve the needs of students who had not been accepted into the district's magnet school, the Academies, but were considered academically above average. Pre-Engineering started with 22 of the school's original 120 students; 20 of whom were to eventually graduate. In AY2006, Pre-Engineering had 22 of the school's 150 9^{th} grade students.

The most rigorous math/science sequence was designed for students in that program: a program designed to prepare students to go on to college majors that require a high level of analytical ability. While engineering represents one of those fields, students in this program also choose to go on to study medicine, law, etc. In addition to their rigorous math and science courses, students in Pre-Engineering take one or more Project Lead The Way (PLTW) engineering courses each year. Pre-Engineering students represent about 10% of the school's population.

The initial program design for Pre-Engineering called for its students to take a traditional science sequence, biology-chemistry-physics, and begin a traditional math sequence with geometry. The belief was that these students would already have completed algebra and would be relatively advanced in terms of their academic abilities. However, it turned out that only 6 of the 22 students had studied any algebra prior to 9th grade. To accommodate this reality, the decision was made to add algebra and physics to their 9th grade program, while retaining geometry and biology. It was felt that the combination of physics and algebra would allow them to progress more quickly to the level that they would need to reach if they were to go on to engineering school.

There were two hours per day reserved for their vocational/technical study. These additional two subjects were taught in that block of time, along with an engineering course, Computer Aided Design. However, the amount of time available for either Biology I or for Physics I was less than would normally be given either subject: they were each taught for about 180 minutes per week. This remained the 9th grade math and science program for Pre-Engineering students for the first three years of the program, from AY2000 to AY2003.

During those years, the 10th grade science courses for Pre-Engineering students were Chemistry and Physics II and the 11th grade courses were Biology II and Chemistry II. In addition, students had the option of taking AP science courses in their third and fourth years. It was felt that Physics II, Chemistry II and Biology II were needed to bring these students up to the level required to succeed in engineering schools and on AP exams.

In AY2004, Biology I was moved to 11th grade, becoming Biology, and Physics I became the sole 9th grade science course. This had a number of benefits: it had become clear that biology could be taught more effectively after students had finished a year of physics and of chemistry; the time gap between 9th grade Biology I and 11th grade Biology II was counter productive; and more academic time was needed for other subjects in 9th grade.

When Biology I moved to 11th grade, Biology II was eliminated as a course. Students interested in studying additional biology were encouraged to take AP Biology in 12th grade and/or Anatomy and Physiology, in 11th or 12th grade, as electives. Also, as we had gained more experience with the courses, it was found that interested students could take AP Chemistry directly after Chemistry I and that disinterested students did not profit from Chemistry II; so Chemistry II was eliminated. In AY2005, a successful experiment, replacing Physics II with AP Physics B for four 10th grade students, was conducted. Based on that result, Physics II was eliminated in AY2006: interested students are now encouraged to take AP Physics as early as 10th grade. This last change marked the end of all non-AP second year science courses.

This brings us to the current AY2006 science sequence. The current sequence requires all students take physics in 9th grade, chemistry in 10th grade and biology in 11th grade. Students who get a B in any of those courses, or who get permission, are allowed to take the second year AP course in that subject. As of this writing, the 35 students taking AP Physics B in 10th grade seem to be doing at least as well as their 11th grade classmates, most of whom took Physics

II last year. The full effect of the elimination of Physics II will not be felt for 2 ½ more years: at that point the current 10th grade students who are taking AP Physics B will be graduating. It is expected that the current sequence will significantly improve their participation and performance on science and math AP exams.

As the Pre-Engineering program evolved; we began applying what we had learned to the rest of our students. Initially, in AY2000, the science sequence for the rest of the school was the traditional biology-chemistry-physics. However, as the benefits of teaching physics to the Pre-Engineering students in 9th grade became clear, we decided to try to obtain some of those benefits for the rest of the school. In AY2002, we made physical science the 9th grade science for most of our students, with biology being moved to 11th grade. This was extended to all students in AY2003.

In AY2003, students in the traditional vocational areas who had above average prior achievement in mathematics began studying Conceptual Physics instead of Physical Science; Conceptual Physics effectively becoming the Honors 9th grade science for traditional vocational students. As a result, there were three levels of 9th grade science being taught in the school in AY2003 and AY2004: Physics I, Conceptual Physics and Physical Science. Only Pre-Engineering students were allowed to take Physics I as they were the only students with time in their schedules to take Physics II.

In AY2005, we rewrote the curriculum for Physics I, renaming it Physics Honors, and made it available to all students with above average math achievement. One goal was to reduce the amount of tracking in the school. The curriculum was revised so that that course could serve as the prerequisite to Physics II or as a standalone. Also in AY2005, Physical Science was eliminated: when Physics Honors became the 9th grade honors science course for all students, Conceptual Physics became the standard course. This change gave students a full year of each science, not ½ a year of physics and 1 ½ years of chemistry: this better balanced the time students studied each discipline and was preferred by both the physics and the chemistry teachers.

In AY2006, Conceptual Physics, based on the Hewitt text, was eliminated and replaced by Physics, based on the same Giancoli text used in the honors course. It was decided that students would gain more by learning the same material schoolwide than by learning different curricula from different texts. The only difference between the two courses became the level of difficulty of the mathematics used: the honors course deals with more mathematically challenging problems.

The evolution of the 9th grade science course is shown in the charts below. For clarity only the physics course taken by the Pre-Engineering students in 9th grade is shown for the years where they took both biology and physics, AY2000-AY2003. Also, the figures for Physics I and Physics Honors have been combined as Physics Honors.

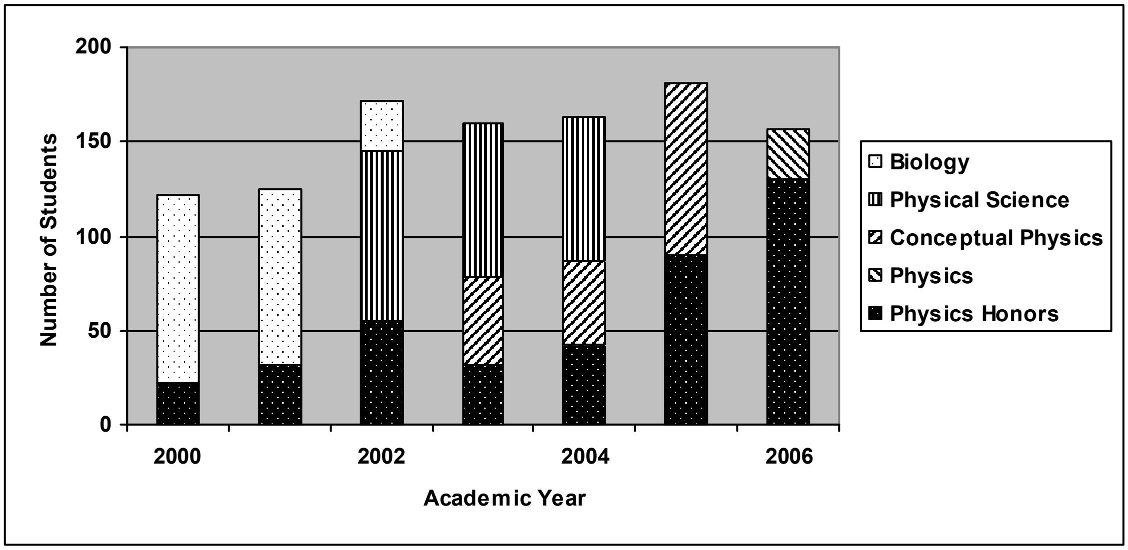


Figure 1: Ninth grade science enrollment by course.

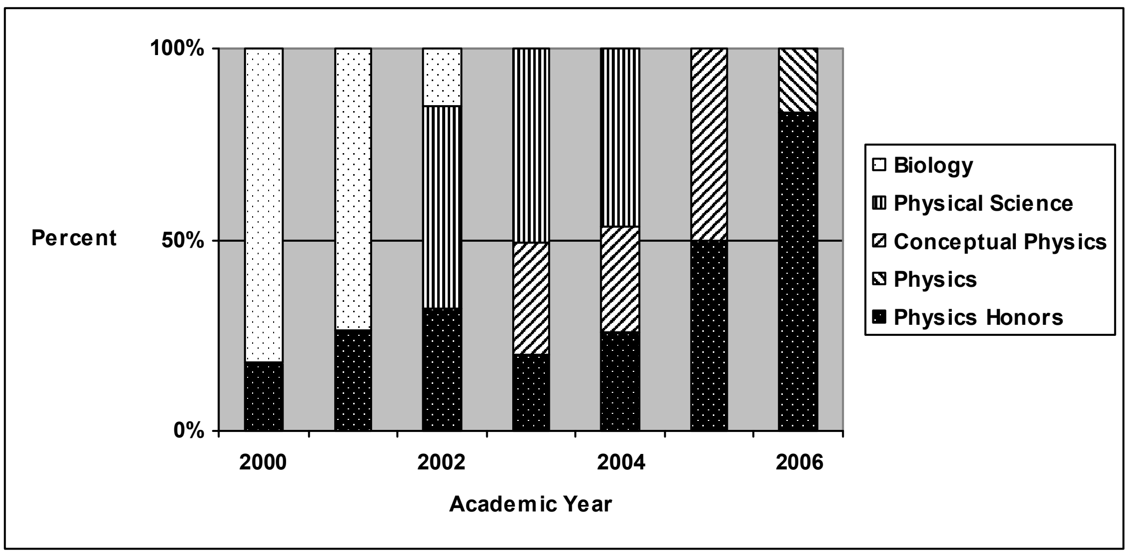


Figure 2: The percentage breakdown of ninth grade science enrollment by course.

There has been debate about whether the small difference between Physics Honors and Physics is worth the price of segregating the students, especially since 83% of the students are now in the honors course. Using a social constructivist approach, the weaker students might be better served by being integrated into the same classes as the stronger students. As a result, there is serious debate about having all 9th grade students take Physics Honors next year; eliminating tracking in first year science altogether. This might well lead to eliminating tracking in the later years as well.

There has been a positive student reaction to the Physics Honors course and a great interest in going on to study AP Physics. When recently asked to sign up for the elective AP Physics B course, about 100 of the 125 students in Physics Honors asked to take AP Physics B along with Chemistry in their second year; only 22 of these students are in Pre-Engineering. The only obstacle is that many of their vocational programs do not currently have the flexibility to accommodate students taking two science courses in 10th grade. If this cannot be addressed, those students will have to wait until 11th grade and would need to choose between AP Physics and AP Chemistry.

With the elimination of Physics II, Chemistry II and Biology II, the second year of study within any science became elective for Pre-Engineering students: students could fill that space in their schedule by electing to take an AP math or science course or additional engineering, computer programming or digital media courses. On the other hand, students in other programs, such as Cosmetology, Automotive, Fashion Design, etc. were given the choice to take the Pre-Engineering math/science sequence as well as any of the AP courses.

One result of this is that students interested in AP courses may take them regardless of their choice of career major and those in Pre-Engineering are not required to take them at all: all AP courses serve as school-wide electives. The only exception to this open policy is due to the time conflict in 10th grade described above.

Algebra and Geometry in 9th Grade

The school's 9th graders come from approximately 35 different middle schools. Their transcripts indicate that some of them studied algebra and some studied pre-algebra in 8th grade. Since there is no standard state-wide algebra curriculum or assessment, it is difficult to determine what students learned based on the titles of their 8th grade courses. Since algebra is so critical for all subsequent study in math and science, all students are assessed on their prior algebra achievement before being allowed to move on to Geometry. It has been found that more than 80% of entering 9th graders need to take Algebra or Algebra Honors in 9th grade, regardless of their 8th grade mathematics course.

However, students need to take Geometry in 9th grade if they are to study Calculus in high school, a requirement for Pre-Engineering students. As a result, Pre-Engineering students have been, and continue to be, required to take two mathematics courses in 9th grade, typically Algebra Honors and Geometry Honors.

Beginning in AY2005, this option was made available to all 9th graders who had been placed in Algebra Honors, about 80% of those admitted, and about half of those students elected to take advantage of it. This will better prepare them for AP Physics, if they elect to take it, and puts them on track to take Calculus in high school. It also lowered one of the last remaining barriers between the Pre-Engineering program and the overall school.

The Demographic Composition of the School

As described above, the setting for this study is a county-run suburban vocational/technical high school located near a major US city. The school has a total population of about 650 students distributed approximately evenly between grades nine through twelve. The school attracts students that are interested in a technical or vocational education: they must be a resident of the county and apply to the school. Their acceptance depends on their middle school academic results, their admissions test scores and the program to which they apply.

The racial and gender composition of the school over the last five years is shown in Table 2, Table 3 and Figure 3. While the percentage of whites and Hispanics has stayed constant, the Asian percentage of the school has risen about 65% during that period, from 11% to 18% while the black population has been reduced in half, from 13% to fewer than 6%. During that same period the female percentage of the school increased from 38% to 45%. Also during that period, the percentage of students who qualified for free or reduced lunch, based on their family income, dropped from 24% to 13%.

	AY2002	AY2003	AY2004	AY2005	AY2006
Asian	44	78	106	126	115
Black	49	56	55	42	34
Hispanic	94	122	137	152	148
White	200	265	290	325	335
Male	243	325	351	374	344
Female	144	196	237	271	288
Free/Reduced Lunch	93	112	95	99	84
Total	387	521	588	645	632

Table 2: School enrollment by race, gender and lunch status.

	AY2002	AY2003	AY2004	AY2005	AY2006
Asian	11.4%	15.0%	18.0%	19.5%	18.2%
Black	12.7%	10.7%	9.4%	6.5%	5.4%
Hispanic	24.3%	23.4%	23.3%	23.6%	23.4%
White	51.7%	50.9%	49.3%	50.4%	53.0%
Male	62.8%	62.4%	59.7%	58.0%	54.4%
Female	37.2%	37.6%	40.3%	42.0%	45.6%
Free/Reduced Lunch	24.0%	21.5%	16.2%	15.3%	13.3%
Total	100.0%	100.0%	100.0%	100.0%	100.0%

Table 3: Percentage composition of the school by race, gender and lunch status

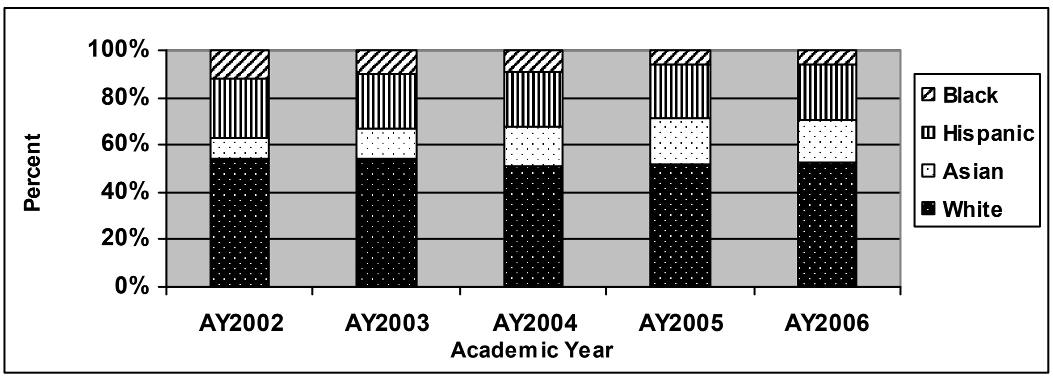


Figure 3: Racial composition of the school by year

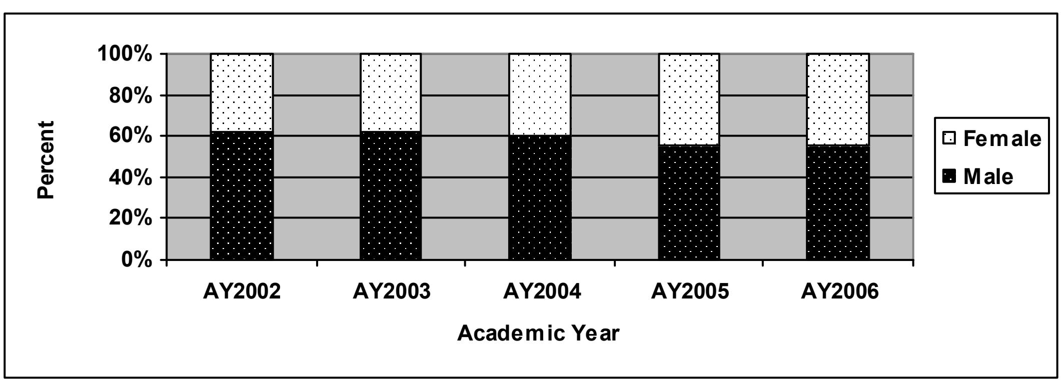


Figure 4: Gender composition of the school by year

In Figure 5 and Table 4 the racial composition of the school is compared to that of the total student enrollments for the state and the county (NJDOE, 2005) for AY2005. Compared to the state, the most significant difference in the racial composition of the school is in the higher percentage of Hispanic and almost equally lower percentage of black students. A similar offset is in the higher percentage of Asian students and the lower percentage of white students. The school also has a higher percentage of boys then girls and the state has a significantly higher percentage of students who qualify for free or reduced lunch, 27% versus 15%.

Some of these differences may reflect the demographics of the county in which the school is located: as a county vocational school all the school's students are drawn from the county and would be expected to reflect the county's demographics. This is the case in the percentage of black students and the percentage of students who qualify for free or reduced lunch: both of those figures are consistent between the school and the county. The percentage of students who qualify for free or reduced lunch is much lower in the county than for the overall state: this probably reflects the higher cost of living in Bergen County.

The lower percentage of females in the school reflects the vocational programs that are offered. However, that figure is moving towards balance and will end the current year at nearly 46%: very close to the county percentage for AY2005 of 48%.

AY2005	School	County	State
Asian	19.5%	14.6%	7.5%
Black	6.5%	6.7%	17.7%
Hispanic	23.6%	14.8%	17.7%
White	50.4%	63.9%	57.1%
Male	58.0%	52%	50%
Female	42.0%	48%	50%
Free/Reduced Lunch	15.3%	12.6%	27.4%
Total	100%	100.0%	100.0%

Table 4: AY2005 racial and gender composition of the school and the state

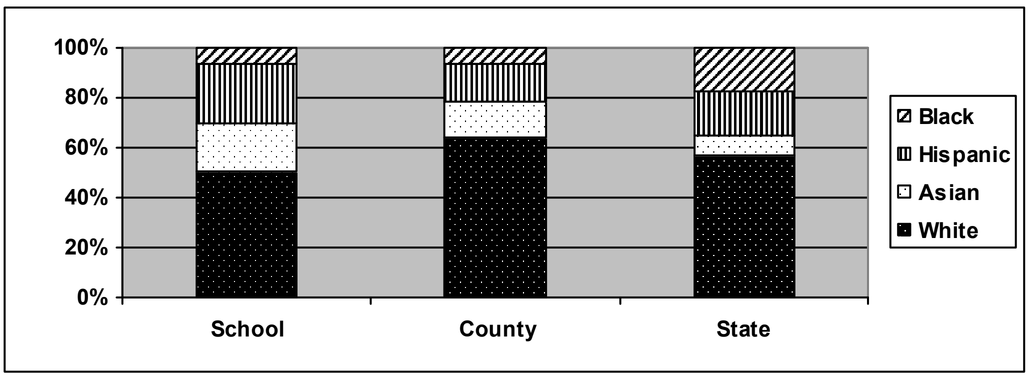


Figure 5: AY2005 racial composition of the school, county and state.

Overall, the school's students were not very different from those in the state or the county: while not identical to either, it is likely that no school's students are, they were not dissimilar in any significant ways. For instance, the school's student body was not comprised of an exceptionally high percentage of demographic groups that are relatively high or low achieving. This proved important to the study as it allowed me to make meaningful comparisons between the performance of the school and the state: comparisons that would not have been meaningful if the demographic composition of the school were unusual.

However, there has been a change in the demographic composition of the school which will provide an alternative explanation of some of the results that will be discussed later. Specifically, during the course of the school's development there has been a marked reduction in its black population and commensurate increase in its Asian population. So while the demographic composition of the school is not very different from that of the county, it does differ from that of the state and it does change from year to year. In addition to examining the demographic composition of the school, it was also necessary to look at the academic aptitudes of the students

The Academic Aptitude of the Students at the School

While I showed above that the demographic composition of the school was not very unusual, that alone would not have made it reasonable to make comparisons between the school and the state. Regardless of their demographic composition, it was possible that the students in the school were all academic superstars with Ivy League goals: that would have rendered meaningless any comparisons to the overall state.

In order to determine if the academic aptitudes of the students in the school would rule them out for comparative purposes, I primarily used their results on the Scholastic Assessment Test (SAT). While this is not a pure assessment of aptitude, it is as close to one as is available on a school and statewide basis. To the extent that student achievement influences the results on the SAT; that would have inflated the apparent aptitude of high achieving students in the school and made them appear to have higher aptitude than would have been revealed by a more pure measure. In this sense, the SAT was a robust yardstick for use in this study as any conflation between aptitude and achievement would have reduced the apparent gap between them and thereby reduced the apparent effectiveness of the program: all errors in this regard would underestimate the effectiveness of the program.

Another value in this measure was due to the availability of both math and verbal SAT scores. As was argued above, I was able to use the students' performance on verbal assessments for comparative purposes since those would not have been affected by the math / science program under study. The SAT proved valuable for showing that the verbal and mathematical abilities of the students were similar enough to make such comparisons valid.

It is also important to understand the background and aspirations of the students in the school. This is a vocational / technical school whose students must declare a major before being admitted: majors span a range from highly technical, requiring a strong foundation in science and mathematics, to traditional vocational. The courses unique to each student's program comprise about 25% of their time in school. In the past, the students' choice of program determined not only their unique vocational courses, but also the rigor of their academic courses; however, the school has been evolving away from making that connection.

A sister school in the same district serves as a county magnet school for the highest achieving students in mathematics, science and engineering. As a result, the students in the school under study, while having achieved above average results in middle school, are not exceptional with respect to their prior interest or achievement in mathematics and science: students who were deemed exceptional in those respects attend the magnet school. In that sense, one would expect that this school would not be fertile ground for science and mathematics achievement. Also, vocational schools are not traditionally strong in their academic performance. However, it is possible that students considering careers in some of the vocations, such as automotive mechanics, electrical or computer science might be more attracted to science and mathematics than to English and social studies. This might or might not be offset by those majoring in cosmetology, fashion design and culinary.

That the students' mathematical and verbal aptitudes are not exceptional when compared to students across the state is seen in the data for their SAT results (see Table 5, Figure 6 and Figure 7). Over the three years of available data the students ranged from being just below to just above the state average with respect to this measure. This is important in that it made achievement comparisons between the school and the state meaningful: achievement comparisons between populations with significantly different aptitudes would have had questionable value.

While there has been a small upwards trend in SAT performance from AY2003 to the AY2005; this result was not directly attributable to the program under study. If it were, there would have been different rates of improvement between student performance on the math and verbal SAT's: the connection of this program to mathematical skill being much stronger than it is to verbal skill. However, the growth rate was almost the same: the average Math SAT (see Figure 6) improved from 496 to 531; the average Verbal SAT (see Figure 7) improved from 480 to 510; this represented improvements of 35 points and 30 points, very similar. During those same years the state average for those tests remained effectively flat; improving from 518 to 519 in mathematics; and from 499 to 501 on the verbal test.

The improvement in these data is more reasonably attributed to the growth in the school's reputation; thereby its ability to attract stronger students. It is important to keep in mind that these data represents different cohorts of students. Thus changes in SAT scores do not represent improvements within a given group of students, but rather, the results of a new group of students each year. Whether these new students were either attracted by the new program or in some way benefited from it while they were in their early grades could not be determined from the available data.

More importantly for my purposes, the amount of growth simply brought the average performance of the population of this school to just above the state average: about 10 points above the state average for performance and about 12% above in terms of the rate of participation on the SAT. This will represent a small effect relative to the achievement data that will be analyzed in this study. (While not directly relevant to this study, it is possible that the increased participation rate on the SAT's was an indirect benefit of the program under study: success in mathematics and science could have affected student interest in going on to college.)

Also, it is important to note that the relative performance of the students in terms of their math and verbal ability was very comparable. They did about as well in terms of their relative verbal performance, compared to the state average, as they did in their mathematical performance. (By AY2005 the students in the school were about 9 points above the state in verbal score and 12 points above the state in mathematics.) This allowed me to examine differences in achievement between areas closely associated with verbal aptitude (i.e. English and social studies) and those associated with aptitude in mathematics (i.e. science and mathematics). Whatever small advantage the students of this school had in aptitude is the same with respect to both their verbal and mathematical aptitudes.

There are three important conclusions that can be seen in these data: the aptitude of the school population, as measured by SAT achievement, rose from being slightly below the state average to slightly above it during those three years; that improvement was relatively the same for both math and verbal; the students' verbal and math aptitudes were comparable to one another when compared to the state.

Scholastic Assessment Test (SAT) Results										
	Students Taking Test		Mathematics				Verbal			
	#	%	Average	Percentile			Average	Percentile		
AY2005				25th	50th	75th		25th	50th	75th
School	126	84%	531	430	530	630	510	430	510	580
State	64612	75%	519	430	520	600	501	420	500	580
AY2004										
School	90	58%	503	420	490	560	484	420	470	550
State	60936	73%	516	446	515	586	499	432	498	566
AY2003										
School	55	53%	496	420	500	570	480	430	480	530
State	60196	75%	518	448	518	589	499	433	499	566

Table 5: School and State SAT Results

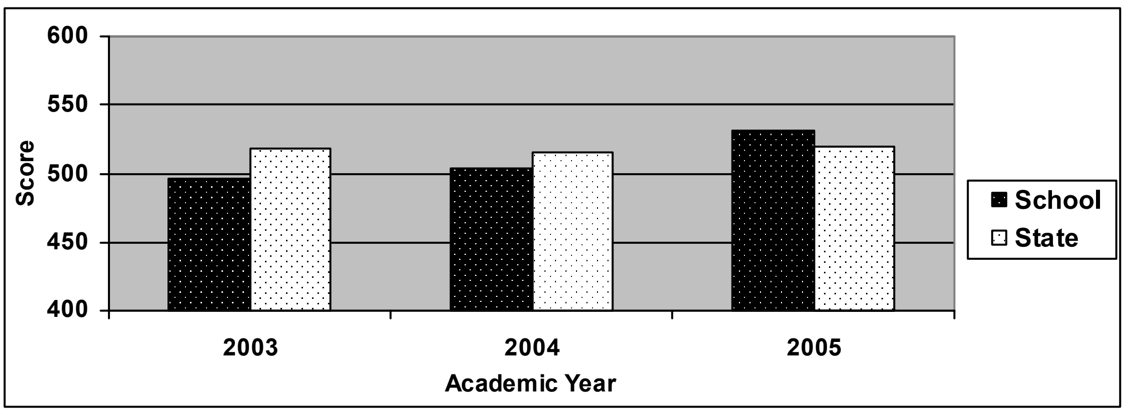


Figure 6: Average math SAT scores for the school and New Jersey.

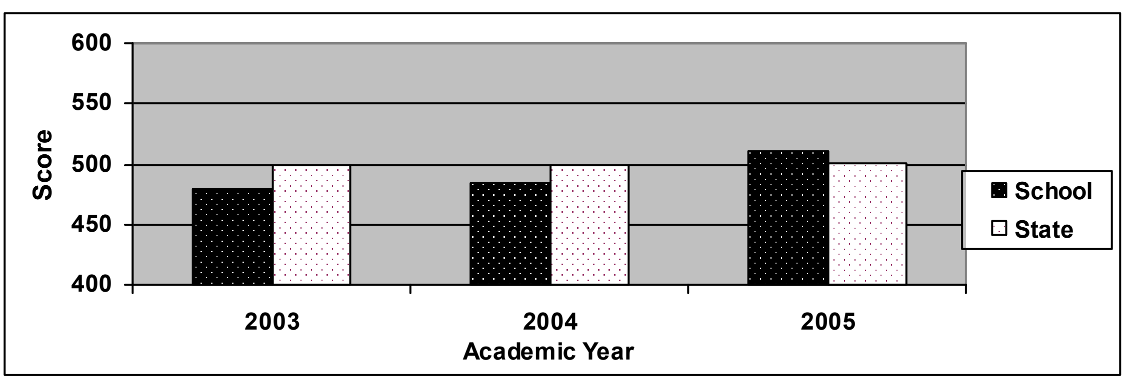


Figure 7: Average verbal SAT scores for school and New Jersey.

It is always difficult to experimentally evaluate programs that have evolved in real-world situations. As a result, there will be limitations on the conclusions that can be drawn from any analysis. In this case, I was able to take advantage of three happy accidents: the school's students were very near the state average in terms of their SAT performance; their math and verbal aptitude were very similar to one another; the English/Social Studies program was relatively traditional and independent of the math/science program. This information was used to establish two baselines for comparative purposes: I was able to compare interdepartmental performance within the school using English and social studies as a baseline and I was able to compare the school's performance to that of the overall state.

These baselines were also used to support each other in order to generate robust results. For example, in one analysis I first normalized the AP achievement of the school, to that of the state, by course and by department. I then compared that normalized achievement data, by department, within the school; effectively combining both external and internal data for comparison. While certainly not experimentally rigorous, these comparisons allowed me to probe the performance of the school by subject area in great detail: these differences in student performance by subject area being critical to this study. I was able to determine if student achievement in science and mathematics was different than in other subjects: a finding that would be a measure of the effectiveness of the program.

Documentation and Analysis

The documentation of the program involved four components.

- The documentation of the science/mathematics sequence; comparison to traditional sequences; and the rationale for the differences;
- The curricula for the 9th and 10th grade physics courses and the rationale for the differences from traditional curricula;
- An excerpt from a chapter of a textbook, currently being written, that mirrors the approach of the ninth grade physics course; and the comparison of its approach to some popular textbooks and the rationale for the differences;
- The description of the six year implementation process of the science sequence.

AP Data and Analysis

I used three types of data for analysis: the results on Advanced Placement (AP) exams, the results on the New Jersey High School Proficiency Assessments (HSPA's) and the participation rates of students in science electives. Statewide detailed information is available for both AP and HSPA performance; allowing me to compare the performance of the school to that of the state. Participation in science electives would serve as a proxy for student interest in science.

A key objective of this program was to increase participation and performance on both AP math and science exams. To determine if that had been achieved, I used the results for the overall state of New Jersey as a baseline for comparison purposes. This was done in four ways. The first three comparisons were done using traditional measures: normalized participation rates, passing rates (scores of 3 or better) and average test scores. However, as I will discuss below, those methods are fundamentally flawed: I propose an additional new measure, which I refer to as the AP Metric, which addresses those flaws.

The problem with comparing participation rates alone is that no weight is given to student performance: schools can improve this result simply by getting students to take the exam, regardless of the effectiveness of their preparation. The problem with examining the average scores alone is the mirror image of the problem with participation rates: schools can improve this result simply by restricting access to the AP exam. By having only the school's top student take the exam the school's average score is maximized. The number of students passing is the best balance between these two, but still suffers from students being discouraged from taking the test if they are deemed unlikely to pass it.

The proposed the AP Metric, described below, provides a balance between participation and performance. It achieves the balance in the following manner: add together the AP scores of all the students and divide by the number of graduating seniors. All students who take an AP exam earn a minimum score of one while non-participants effectively get a score of zero. Thus, increasing AP participation yields a higher score on this metric. However, a score of five have five times the value as compared to a score of one, increasing the performance of participants also increases the overall score.

Dividing by the total number of graduating seniors also normalizes the data so that comparisons can be made with other schools; the overall state; or even between states and regions. This metric can be calculated by individual course; department; school; or state. As a result, this metric yields a normalized weighted measure of AP participation and performance that can be applied at any level of detail.

Statewide data are publicly available for the total scores earned on each AP exam and the number of graduating seniors. Therefore, I was able to use this metric to create a baseline for the state and then compare it with the school's performance. Through that comparison I could determine the relative performance of the school by subject area. This gave me an indication of whether those subjects in which the new program for science and mathematics had been implemented showed differential achievement gains relative to other subjects, such as English and social studies, where such a program is just commencing. Also, since all these data were available from the inception of the program until the present, I could examine and analyze the trends.

HSPA Data and Analysis

Another measure of math achievement used in this study was student performance on required state tests. The math and English High School Proficiency Assessments (HSPA) are given to all New Jersey students in the 11th grade. Students are categorized as being either Partially Proficient (a nice way of saying not proficient), Proficient, or Advanced Proficient. These results are published for all schools and for the total state: they represent a comparative measure of achievement in these areas.

It would have been theoretically possible to apply a value added model to evaluate the effectiveness of the school's programs if individual student data were tracked from school to school so as to allow a comparison of performance on the 11th grade HSPA to the 8th grade test GEPA. However, that was difficult to do in this case as the school's students come from 35 different middle schools and the state does not track data by student. (As the state is now in the process of computerizing their test data an analysis of this type should be possible in the future and would be valuable to do at that time.)

In this study, I was able to do an analysis of the overall HSPA results by assuming that the students in the school were, on average, comparable to those in the state. As was discussed above, the SAT scores of the students in this school are approximately the same as those of students across the state; implying that the student population is not exceptional. While it is true that the very fact that they came to the school results in a selection bias, I was able use a comparison between trends on the math and English HSPA to effectively use English as a control for the math results. However, while this analysis would reveal differences in performance by department, it could not attribute the causes for those differences This will be discussed further below.

Participation in Science Electives

I used participation rates in science electives as a measure of the value the school's students place on the study of science: an effective science program should result in an increase in its apparent value to students. What courses, that are above and beyond what is required of them, students choose to take may indicate either their interest in the material or their belief that it is important. While participation rates alone cannot determine which of these two factors is motivating students, it does measure their combined effect: reflecting the value students place on the study of science.

I only included science courses that were not required by either the school or the student's program of study when doing this analysis. I divided the total enrollment in science electives by the number of graduating seniors to arrive at the participation rate. While not indicating the actual electives taken by seniors graduating that year, this did indicate the current participation in science electives normalized to the number of graduating seniors.

Using this approach gave greater weight to students taking three electives than to students taking one. This had the benefit of weighting student participation but did not give a measure of the total number of students who took a given number of electives: zero, one, two, three, etc.

Since most science electives are AP courses, this measure results in double counting AP courses in that they appear both within this measure as well as within the figures for AP participation. While this represents a conflation of those two measures, excluding AP science courses would be a less reasonable approach since students can only be expected to take a limited number of science course in a given year: if they choose to take an AP science elective they will not have the time in their schedule to take a non-AP science elective. This limitation should be kept in mind when examining these data.

Another limitation is that while I am using this as a measure of the value that students place on science, it also reflects the judgments of their parents, guidance counselors, friends, etc. It is not possible to certain why a student takes one course or another. Also, it might represent a paucity of non-science electives.

Summary

The students in this school were not very different from those in the overall state from the perspective of both their aptitude and their demographic composition: it is reasonable to compare the academic achievement of the school to that of the state. The students in this school were also not very different in terms of their mathematical and verbal aptitude: it is reasonable to compare their achievement in science & mathematics to their achievement in other subjects, such as English and social studies.

Three separate measures were used to determine the students' interest and achievement in mathematics and science: AP results, HSPA results and participation rates in science electives. I was able to use a combination of these three measures to make comparisons to the state and to the school's performance in other subjects to determine the effectiveness of the program.

Based on the effectiveness of the program it was expected that other schools might choose to adopt it. To facilitate this, the program was documented both with respect to its current state as well as its rationale.

CHAPTER 4: RESULTS

The first three research questions will be answered in the first six sections of this chapter. These are the questions that involve the description, documentation and analysis of the science program at the site:

1. What is the new science scope and sequence and how is it unique?
2. What are the new physics curricula and how are they unique?
3. What is algebra-based physics and how is it unique?

The answers to these research questions serve two roles: to determine if the predicate of the hypothesis is satisfied by this program and to describe the program in sufficient detail that interested schools could replicate it.

The final three research questions are answered to the succeeding three sections:

4. How does the AP performance of the students in this program compare to that of students in other New Jersey schools?
5. How does the HSPA performance of the students in this program compare to that of students in other New Jersey schools and to their English HSPA performance?
6. What are the trends in the participation rate in science electives?"

The answers to these questions serve a different role than the first three: they serve to determine if the predicted outcome has occurred and, therefore, if the hypothesis has been supported. This would be straightforward if the sole purpose of answering these questions was to simply describe the outcomes.

However, a purpose of this study is to try to determine the answers to these three questions and the implications of those answers with regard to the hypothesis.

This is problematic since it is difficult to ascribe causality in any complex situation; there will always be alternative explanations that might be the cause of the observed outcomes rather than that which is supposed in the hypothesis. The proposed and the alternative explanations will gain or lose in plausibility to the extent that they are consistent with answers obtained to these final three research questions. However, the answers to these questions will not be sufficient to categorically determine whether only one explanation is reasonable; that will require future research.

For the sake of clarity I will posit several alternative explanations at the outset of this chapter and, in each section where the results are discussed with regard to the hypothesis; the alternative explanation will be considered as well. This will serve to remind us of the limitations of the study. It will also lead to proposed future research that could differentiate between the various explanations. The implications of the range of possible explanations and future research will then be further explored more globally in the chapter five.

- AE1. The growth in the Asian population of the school could account for improvements in performance in mathematics and science achievement as this demographic group has historically performed well in these disciplines.

- AE2. The differential performance between science and mathematics versus English and social studies could be accounted for by the growth in the Asian and Hispanic population. Both these groups have a higher proportion of students that speak English as a second language and may have weaker performance in subjects that require English language skills.
- AE3. Outside factors in the community or internal factors, such as the influence of guidance counselors, etc. could be playing a role.
- AE4. Apparently high performance in mathematics and science as compared to English and social studies could reflect weakness in the English and social studies programs and/or the faculty in those departments rather than strengths in the science and mathematics program.
- AE5. The performance of the mathematics and science program might be due to other strengths in those programs, not related to the hypothesis, or it could be due to the strength of the science and math faculty.
- AE6. As a vocational / technical school, this site could be particularly fertile for mathematics and science and the opposite might be the case for English and social studies.

An Overview of the Science Program

The new science program is comprised of nine courses: three first-year courses, in physics, chemistry and biology, three honors-level courses in those subjects, and three second-year courses that culminate in the AP exam for that subject. The first-year courses can serve as either standalone courses or the first half of a two-year AP sequence.

This was accomplished by making the first-year course objectives a subset of the AP curriculum's objectives. (The key differences between the regular and honors level courses are the speed at which new material is introduced and the mathematical depth to which it is studied.) Most students who want to go on to take the AP course in the second year are allowed to do that. They are automatically admitted if they attain at least a B in the honors course or an A in the standard course. Even if they do not have those grades, they can get permission if they express a strong interest and a willingness to make an extraordinary effort.

If students do not want to take the AP course, they still benefit from the challenging first-year course: they are prepared for further study in college or university. While every introductory university course is unique, the AP course is constructed to reflect a broad survey of first year courses taught across the country. While this certainly does not mean that it is the best course, if it were it could not also represent a typical course; however, it does represent a target for what a student might encounter upon entering a random American college or university. Therefore, the same first-year high school physics course that prepares students for the AP course should also prepare them for the typical introductory course at an undesignated college.

Whenever more than one section of a course is offered, more than one teacher is assigned to teach it. While this increases the number of different courses for which each teacher must prepare, it also creates a team of collaborative teachers who work together on updating curriculum materials as well as sharing what has proven effective in teaching with that material. Often, teachers are responsible for a section of the first-year course and the subsequent AP course, giving them a sense of direction for the combined two-year sequence.

The teachers for each course work together to design common summative assessments (unit tests, midterms and finals); worksheets: formative assessments: lab activities: etc. For the most part, summative assessments are all given on the same day school-wide. This set of common summative assessments, assessment dates and curricular materials results in greater efficiency; gives students a sense that there is a purpose and direction to their studies; allows students to study together and tutor one another, regardless of teacher; increases student and teacher morale; and, thereby, improved student achievement. By assuring that each student has the same high level of preparation, the goal of maximizing the number of students who go on to take the AP course, and then successfully take the AP exam, is achieved.

The New Science Sequence

Answering the first research question requires a detailed description of the new science scope and sequence. A key element of the new science program is the reordered science sequence: physics is taught in ninth grade instead of biology; biology is taught in eleventh grade; and chemistry remains the tenth grade science. While this new sequence, and the course curriculum changes that follow from it, are in the sciences, a key goal of this approach is to benefit mathematics education as much as science education.

	9th	10th	11th	12th
Science	Physics	Chemistry AP Physics B (optional)	Biology AP Chemistry (optional)	AP Biology (optional) <u>Electives</u> AP Environmental AP Physics C Anatomy & Physiology Earth Science Modern Physics Forensics
Math	Algebra Geometry Honors	Math Analysis I	Math Analysis II	AP Calculus AB (optional) <u>Electives</u> Calculus AP Calculus BC Statistics

Figure 8: The new scope and sequence.

This sequence uses each science to scaffold the understanding of the next. Physics establishes the basis for chemistry while, together, physics and chemistry build a foundation for biology. This bottom-up approach allows each science to be taught in a manner that stresses reasoning over description and memorization. Implementing this approach requires each curriculum to be rewritten to take full advantage of the foundation that has been established the prior year.

A key objection to this approach is that ninth grade students do not have the mathematical background to learn physics. One solution would be to teach physics in a conceptual rather than a mathematical manner: however, this would eliminate the mathematical foundation of physics. Mathematics is as much a foundation to physics as physics is to chemistry and chemistry is to biology. To achieve the full benefit of this reordering, mathematics must be used to establish the basis of physics.

However, that mathematical foundation can be established through algebra alone. Algebra is commonly taught to ninth grade students and, increasingly, to students in Middle School. While mathematically oriented physics books use trigonometry, which is rarely understood by ninth grade students, the use of trigonometry is not essential to the goal of establishing the mathematical foundation of physics. It is associated strongly with first-year physics only because eleventh grade students, who were taught physics in the old sequence, had already mastered it anyway and, as a result, that is how textbooks and curricula have been written.

At the same time that algebra is establishing the foundation for physics: physics is the ideal setting for students to improve their mathematics. First, students double the number of hours spent each week practicing mathematics. Second, physics demonstrates to students the usefulness of mathematics, both in terms of being able to solve physics problems as well as the real-world applications described in those problems. Third, real-life applications of algebra to the solving of physics problems give mathematics a context and thereby increase its meaningfulness to students, making it less abstract.

Analysis of Curriculum Articulations

Understanding the articulations between the courses in the new science scope and sequence is also related to the first research question. The connections between courses are critical to the success of any school-wide curriculum: those connections are illustrated in the following diagram. An arrow connecting two courses shows that what is learned in the first course is used in the target course. A double headed arrow shows that the learning in each course is applied in the other. It is important to keep in mind that applying what is learned in one course actually benefits both. The usefulness of that learning, as it is applied in the second course, actually gives it additional meaning; makes its usefulness clear; and gives students an opportunity to practice. So, while the target course clearly benefits by the prerequisite knowledge which the student brings with them from the first course, the first course benefits as well.

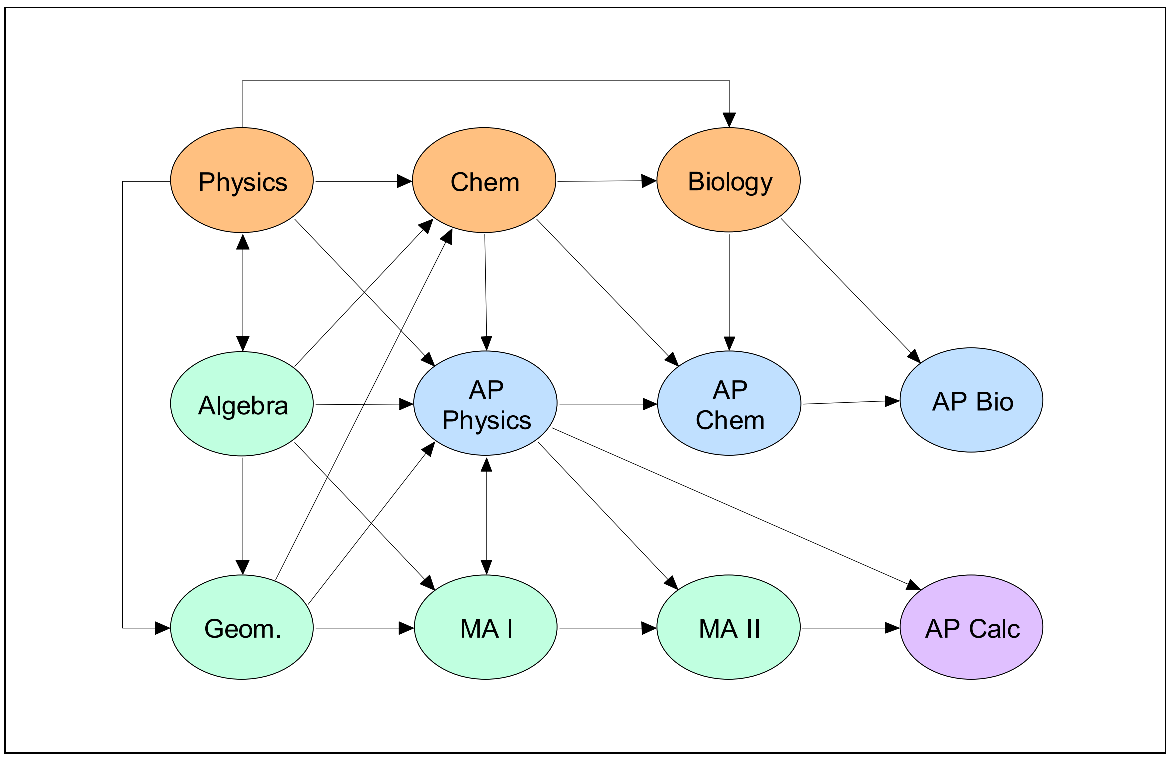


Figure 9: The curriculum articulations of the new scope and sequence.

This diagram makes clear the web of connections that are made between each of the sciences and between science and mathematics. These connections take a variety of forms which may be ascribed to the categories of factual / conceptual, procedural, process and metacognitive.

Factual / conceptual connections take the form of specific knowledge that is learned in one course and used in another. For instance, a number of the concepts learned in 9^{th} grade physics are prerequisite for understanding chemistry: energy; atomic structure; force; electric force; etc. Similarly, much of what is taught in chemistry and physics is required for biology. Modern biology is based on an understanding of the physical world. Without an understanding of chemistry, energy, and electric forces; a cell makes no sense; and the cell is the basis of modern biology. As was discussed in chapter one, the flow of scientific knowledge is consistent with the arrows shown in the above diagram (Haber-Schaim, 1984).

Procedural connections represent instances where a specific procedure that is learned in one course is used in another. Examples from 9^{th} grade algebra include solving linear equations; graphing; scientific notation; graphical analysis; etc. These are taught in algebra and then used extensively in physics and, to some extent, geometry, giving students a chance to practice what they have learned and reinforcing its usefulness: supporting the learning of algebra. They are then used in subsequent and parallel mathematics and science courses.

Process involves the variety of ways that students learn to explore the world: inquiry; large group problem solving; small group problem solving; hypothetico-deductive thinking; etc. These are taught extensively in the ninth grade physics course and represent a major goal of that course. These process skills are then used extensively in the science and mathematics courses.

Metacognitive relates to learning about the process of thinking and learning. This is strongly emphasized in the ninth grade physics course as complex multi-step problems are solved: problems that involve a great deal of reading and understanding prior to employing procedures. For instance, students are taught how to read problems at least three times: one time to get a general understanding of the problem's structure; a second time to identify and record pertinent information and develop a strategy; and a third time after its been solved to see if the question has been answered and if the answer is reasonable. They are taught how to monitor their deployment of problem-solving strategies to make sure that they are self-consistent and consistent with their goals. The skills of metacognition are useful in all their other courses.

The arrows in the diagram above indicate this logical flow of concepts between the different subjects. The flow between the sciences does not exist in the reverse direction. It has been shown by the analysis of Haber-Schaim (1984)that there is little learned in biology that is prerequisite to chemistry or physics and similarly there is little learned in chemistry that is prerequisite to physics. Also, there is no connection between a 9th grade biology course and mathematics.

As a result, the web of connections is very much reduced in a traditional scope and sequence; even one that is considered rigorous. Also, in a traditional sequence any connections that are made are delayed until the student's later years; after they have been tracked towards or away from math and science. This is shown below for purposes of contrast. Note the lack of connections between the science courses and that the connections to algebra are not made until after 9th grade, too late for many students.

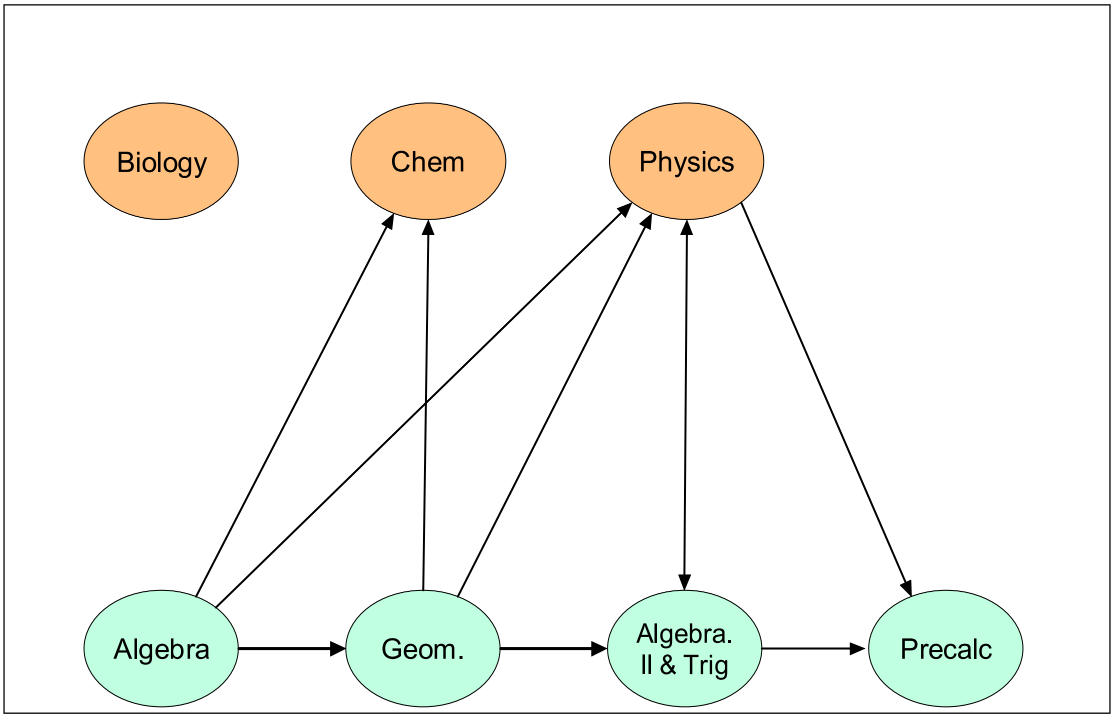


Figure 10: The curriculum articulations of a rigorous traditional scope and sequence.

In the case of this "rigorous" curriculum the connections between science and mathematics are both much reduced and are made after 9th grade. By the end of 9th grade, most students will have been tracked into one sequence or another, so the benefits of imparting meaning to the mathematics due to the science courses will come too late. While the addition of an AP Biology course in the fourth year will improve the number of connections; these are established very late in the sequence and those connections, especially between Biology and AP Biology will be tenuous. Adding AP Physics as a fourth year science will create stronger connections, due to the more recent teaching of Physics, but many students will already consider physics to be “hard” due to the weak mathematical foundations established in their early years. Only those already pre-selected as “strong” math or science students are likely to view AP Physics as a viable option.

A much worse, and much more common example, of the problems due to a traditional science sequence can be seen in the below diagram. Students who are identified as “weak” in math are often given just two science courses. The first year course is Biology, Earth Science or Physical Science. While the last of these would be better than the former, it is usually taught in a relatively non-mathematical manner, decreasing its potential benefit. Aside from the lack of science in this sequence, this approach leaves mathematics very much weakened. There is very little opportunity to apply what is learned in mathematics in another context. The students who would perhaps gain the most from the new sequence are those with the weakest math skills at the beginning of 9^{th} grade. Those are the same students who probably gain the least from the minimal version of the traditional sequence.

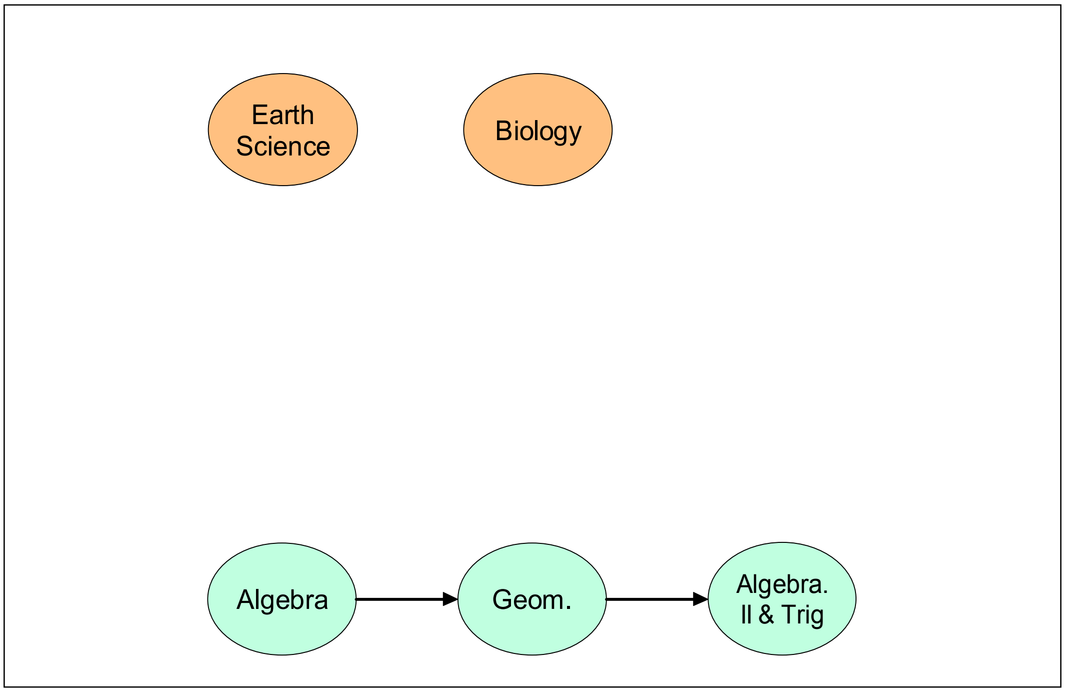


Figure 11: The curriculum articulations of a minimal traditional scope and sequence.

In contrast, even in the minimal version of the new sequence, shown below, there are a strong set of connections between the sciences and between math and science. Importantly, that web of connections is strongest in the 9th and 10th grades, before students are tracked away from mathematics and science. This set of connections is critical for students who have not seen the importance of math and science prior to reaching high school. This is an important opportunity to have the meaning and usefulness of those disciplines made clear to them; while all their future options in math and science are still open.

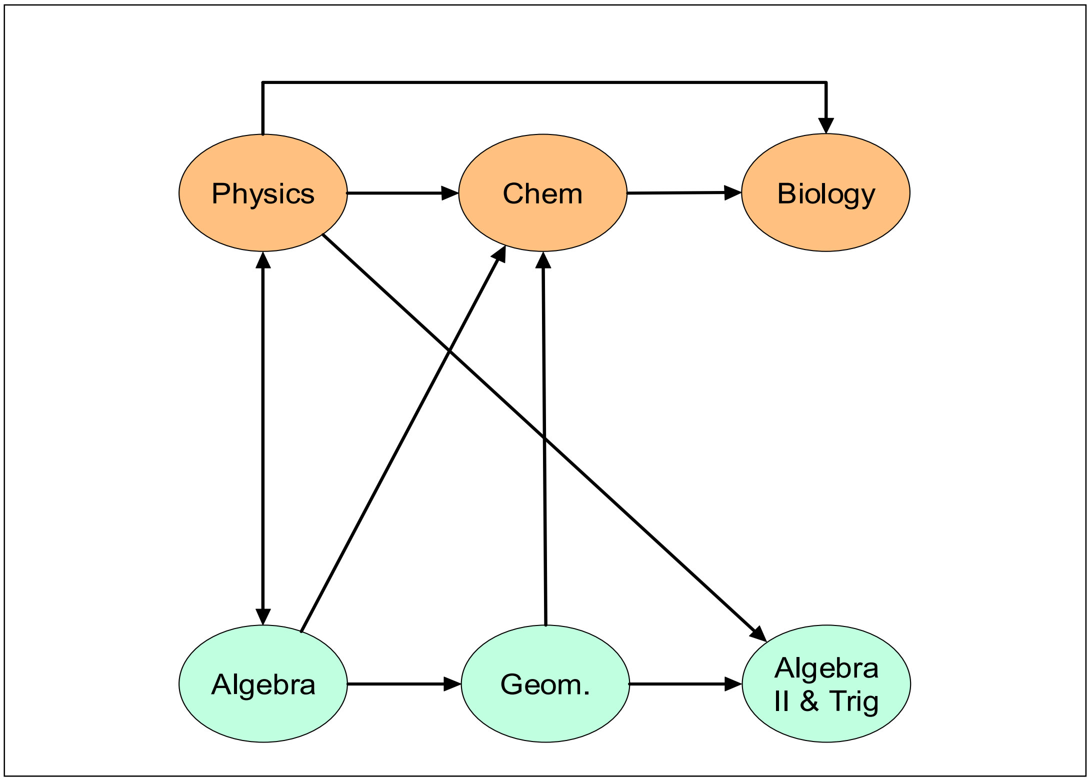


Figure 12: The curriculum articulations of a new minimal scope and sequence.

The benefits of this approach should be most visible among groups who have typically been underrepresented in math and science: minorities and women. These groups are more likely to have been steered away from math and science prior to their arrival in high school. A program that minimizes tracking and gives all students a solid foundation will benefit most those who are least likely to have been given that foundation in their earlier years.

Importantly, there is little difference between the least and most rigorous version of the new science sequence in 9th grade; only the second math course. As a result, any students that do find a new interest in math or science, due to taking those 9th grade courses, can participate in the most rigorous science sequence; the only obstacle they will need to overcome is learning the basic trigonometric functions on their own or after school. In general, this approach leaves all the students “in the game” a year longer; giving them a chance to find their interest in math and science.

Implementing this approach required rewriting the curriculum of each course. For example, there are no physics texts, or curricula, that use an algebra-based approach: they are either non-mathematical or require trigonometry. Neither approach would be effective for the ninth-grade physics course. A second example is that biology is taught very differently to students who have a background in physics and chemistry than to ninth-graders who have no such background. However, in this case, biology texts and curriculum exist in the form of the AP curriculum and supporting texts.

The 9th Grade Physics Course

The second and third research questions directly relate to the physics curricula. While appendixes A and B directly answer that question by providing those curricula, a more in depth understanding of the 9th grade physics curriculum is provided in this section. This course is the keystone to the new science/math program: without it the program could not stand. It serves as the foundation for all the science courses that follow while providing the context within which meaning, usefulness and practice are provided to mathematics. It is uniquely structured with the aims of promoting transfer between algebra and physics; creating a foundation for chemistry; creating a foundation for AP Physics B; and developing problem solving skills.

This is accomplished by using a social constructivist approach that takes advantage of the flat playing field offered by physics. While prior student achievement in mathematics varies, none of the students have previously studied physics. Since the mathematics used in the physics course is restricted to algebra, it is within the reach of all students. It is the case that some students have a stronger background in algebra than others: some have even placed out of Algebra and into Math Analysis I. On the one hand, that does not give those students a direct advantage, since only algebra is used in the physics course: on the other hand, their stronger background in mathematics puts them in a position to help those students who are weaker in mathematics.

The three pillars upon which the course is built are inquiry, hypothetico-deductive reasoning and problem solving. Inquiry is used to construct new concepts; hypethetico-deductive reasoning is used to develop the practical consequences of those concepts and test them; and problem solving is used to explore and practice the use of those concepts in a range of theoretical problems.

Maintaining a proper balance between these three pedagogical approaches is critical to the success of the course. Once a new concept is constructed and given meaning it must be shown to be useful or it will seem isolated and irrelevant. Once shown to be useful: it must be practiced. Once a concept is firmly established, it must be used in building the next concept: providing a foundation for the new concept while having its own usefulness reinforced in the process. The knowledge that students construct leads to new knowledge; dead-ends are eliminated; learning is made useful.

Inquiry and hypethetico-deductive thinking can take many forms in the course depending very much on the concept being developed and how directly connected it is to prior understanding. If the new concept simply represents an extension of prior learning being applied in a new context, or combined with a new piece of information, it might be done by posing a question to the class and reasoning to a conclusion through dialogue, a process that could be accomplished in just a portion of a 40 minute class. In other cases, it might require a full class period, or even an 80 minute lab period. Let us consider a case where the students have recently developed the kinematics equations.

At the beginning of a subsequent double period lab class the teacher might briefly tell the story of Aristotle's idea that objects fall at a constant velocity versus Galileo's idea that objects fall with a constant acceleration. A description of Galileo's inclined plane experiment setup would then lead to a discussion of the different predictions that would be made for that experiment by applying Galileo's theory versus Aristotle's: the shape of the graphs that would result and their implications. This would draw on the understanding that the students had developed with regard to both kinematics and graphical analysis.

The students would then do the experiment; make the graphs; and reach their own conclusions. While they would not have a sufficient understanding of trigonometry to use their data to derive the value of g as 9.8 m/s^2, they would be able to show that a cart constantly accelerates as it rolls down an inclined plane. This is a big conceptual step, but is directly linked to their prior learning of kinematics: without that prior learning this experiment would have no meaning. This approach is similar to the ISLE cycle of Etkina and Van Heuvelen (2001).

In the next class, the teacher might provide the value of g; drop a pencil from a height of 1.0 m; then ask the class how long it was in the air. Although there are no new concepts required; solving this problem requires transferring their prior learning of kinematics to a new type of problem, falling objects. This task would typically start a very active set of discussions and work by the students. The toughest job for the teacher is to keep out of it; not tell the students how to solve it; let them figure out how they could use what they have learned before. This single problem might occupy much of a class period.

In other cases, a class period might be used to apply prior learning to solve new, more complicated, problems. For instance, if students have been previously learned to solve problems involving an object being pulled across a frictionless surface by a second hanging object; and more recently they have learned how to determine the frictional force acting on an object being pulled along a surface; they might use a class period to combine those ideas in order to solve problems involving a hanging object pulling a second object across a plane where friction is a factor. This does not represent a new concept; but it does represent a challenging problem that engages students and reinforces prior learning.

Beginning a completely new subject requires an even more extensive introduction. For instance, when beginning the topic of electric charge and force, a more open-ended inquiry lab might be done where students probe the forces of attraction or repulsion that exist between different materials: rubbed glass rods with rubbed glass rods; rubbed glass rods with rubbed plastic rods; rubbed plastic rods with rubbed plastic rods; rubbed glass with aluminum cans; etc. This initial work towards the construction of a new concept would occupy a full double period lab: the class would need to construct a range of fundamental ideas before they can be used to solve problems.

Once a new idea has been constructed; problems using that new concept are worked through. The teacher may show what type of questions can be answered using this new concept and work through a couple of examples. The teacher would then pose similar problems to the class and they would work through them together. In this case, the class would work together as a large group, with the teacher as moderator and recorder, for about ten to fifteen minutes in order to solve two or three variations on that type of problem: the students would contribute all the steps. Every student would contribute a step to solving a problem once or twice each day in this setting. In a class of twenty, that means that the class make about 20 to 40 contributions to solving a problem over a time of less than fifteen minutes, a relatively fast pace. This keeps the class fast moving and all the students involved. Alternative methods of solving the problems might also be volunteered by the students or teacher in this setting.

The students would then spend the remaining fifteen to twenty minutes of the class solving problems in small groups of threes or fours. This is very consistent with the approach described by Heller (Heller, Keith, & Anderson, 1992); (Heller & Hollabaugh, 1992). The students sit at round tables and are given worksheets with problems that are designed to escalate in difficulty. They quickly reach problems which require them to consult together. The first part of the class allowed them to construct some basic understanding, skill and context. The latter part of the class uses what was learned and builds on it to get the students into their Zone of Proximal Development (ZPD) for the maximum amount of time: this is where the development of the student should be most effectively accomplished.

The teacher monitors student progress and encourages students to work together around their own table or consult with other tables as needed. The teacher's primary role during this process is to work with the students just enough to keep them in their ZPD. This is an art: the teacher must have a sense of the class dynamic in order to offer just enough help and advice to keep them moving forward, but not so much as to eliminate the challenge. If progress is too slow, frustration will take them out of their ZPD: if progress is too rapid, they will not be advancing their development. The students' struggle to solve problems is critical to their learning. But if they give up the struggle, due to frustration, nothing is gained: the teacher's job is to intrigue them with hints; encourage them with praise; and cajole them to continue struggling until they achieve the success that everyone in the room must believe is within reach, but just barely.

This is a relatively noisy environments with students actively engaged at the limits of their ability. Once a student has completed all the problems, that student puts the first one on the board so that the class can agree on whether it is correct. Although the students cooperate in solving many of the problems, there are typically students who both provide their peers with the most help and finish most quickly. This continues until all the problem solutions have been shared and agreed upon. No student puts more than one problem on the board.

A set of problems of similar difficulty represents their homework. While they are free to work on these either together or alone, they should have developed the skills, during class, to solve them by themselves at home. Homework is for the benefit of the students and is reviewed only at their request the next day.

By working together in groups to solve problems, the students learn physics together while teaching each other a deeper understanding of algebra. Both those who begin the year weaker in mathematics and those who are stronger benefit, but the benefit takes different form. Those who are stronger gain by the opportunity to practice and explain while those who begin the year weaker gain by being tutored and by seeing the meaning and usefulness of mathematics. By establishing an environment where students can learn together and teach each other physics, while making use of their different relative strengths in mathematics, all students learn physics and improve their ability in mathematics.

A crucial element is the creation of an open atmosphere where students are free to ask questions without being embarrassed and all the steps to solving problems are discussed explicitly. If dividing both sides of an equation by the same number is a step in solving a problem, it is explicitly shown. In that way, no student is singled out for not understanding even the most basic steps, since all steps are shown until it is absolutely clear that every student understands them. The class needs to be fast paced, fun and non-critical.

Informal ungraded formative assessments (Black & Wiliam, 1998) are occurring constantly throughout the time in class. There is a high level of student-teacher and observed student-student interaction so the level of student's ability to solve problem and answer questions is generally clear. Weekly, there are graded quizzes or quests (full period quizzes) that represent spot checks of whether students are able to apply their knowledge to solving problems on their own. These quizzes are at about the same level as the student homework. No grades are given for homework, class participation, projects, etc. Only demonstrated ability to answer questions or solve problems in the presence of a teacher is graded.

Summative assessments take the form of chapter tests, midterms and finals. These are all given in the same form as the AP exam: half multiple choice and half free response. The multiple choice questions are conceptual in nature while the free response involves solving multi-step problems, often taken from prior AP exams. The identical summative assessment is given to all the students in the course on the same day, regardless of their teacher.

Common assessments and assessment dates enable and encourage students to study together in groups, with or without a teacher, to advance their skill and understanding: they help engender a culture in which physics is a common topic amongst all the students. This is the opposite of the effect of tracking, in that it bonds students rather than separating them.

This atmosphere is supported by the availability of after-school opportunities to study. In fact, a critical element of the course is that teachers stay after school for two hours twice a week throughout the year. During this time, students are encouraged to work in groups, with or without the teacher, to advance their understanding. Students who have taken the course in previous years often work with those groups as informal tutors. While this continues on a steady basis throughout the year, an upcoming test tends to generate large numbers of students who enjoy eating pizza and studying physics in a festive environment. This has become a part of the school culture; attracting students in all grades that enjoy the chance to help and be helped.

The opportunity to study after school is a critical element in reducing the amount of tracking in the school. This extra time is necessary for students who might otherwise not be able to succeed in such a challenging course: at the same time, it reinforces the learning of the stronger students.

Students who are not satisfied with their grades on any assessment are also welcome to come after school to study with others and, when ready, take a new version of that same assessment. The idea is not to “catch” the students through testing, but to make sure that they have the necessary skill and understanding to proceed. This also helps generate a positive atmosphere in the school: students see that the teachers care about whether they learn: teachers are taken out of the role of adversary. Students can improve their grade through better mastering the material. On the other hand, extra points are not given for “effort” in the form of posters; homework; reports; time spent after school; participation; etc.: only for demonstrated understanding on assessments.

It is important to note that the focus of this course is only partly to teach physics content: key goals of the course include developing problem solving skills and improving achievement in mathematics. These goals are consistent with the survey results cited above (Van Heuvelen, 2001) in that even most physics majors found that physics content was the least useful thing they learned by studying physics: problem solving was the most important.

Viewed from this perspective, many of the issues, such as “misconceptions”, considered primary by some in the field become a lower priority: it is much more important that students learn how to reason clearly and have a positive experience that encourages them to continue studying science and mathematics. Without that further study, little of the physics content will be retained in any case. However, the ability to reason through problems will continue to be applied and has a much higher chance of being retained by students. Also, if students have a positive experience, they are more likely to study more physics in the future, which further deepen their understanding of concepts.

In summary, the teacher’s role in this course is primarily to establish a non-critical environment in which students can construct physics concepts; learn to solve problems; improve their achievement in mathematics; and enjoy science. Ideas are introduced using an inquiry approach grounded in demonstration and discourse; tested using hypethetico-deductive reasoning; and reinforced by being used to solve problems. While the teacher provides the information necessary to construct those ideas, students are not left to "discover" them: this is done in a way that virtually eliminates lecture from the course. Instead, phenomena are shown to the students and the ideas are developed through discourse. Once ideas are constructed, they are used to solve problems and construct higher level ideas. The vast majority of the year is spent by students working together in groups solving problems, an activity that they enjoy. Everything about the way that the course is conducted stresses student learning over all else.

The 9th Grade Physics Text and Curricular Materials

The following more detailed description, in this and the following section, of the proposed text and curricular materials for the 9th grade course expands on the second and third research questions. A unique aspect of this physics course is that it is strongly tied to using and developing algebra skills but does not require any trigonometry. Most physics courses are either conceptual in nature, such as those based on Hewitt's *Conceptual Physics* (2002), or require the use of both algebra and trigonometry, such as those based on the text written by Giancoli (1998). It is assumed that students are either too young to employ mathematics effectively or, if able to do so, are older and would know both algebra and trigonometry. The students in this course fall into neither of those categories.

Since no textbooks are written to support the approach taken in this course, it was necessary to choose whether to add the algebra content to a conceptual text or subtract the trigonometry content from an algebra/trigonometry based text. It was judged easier to subtract than to add, so Giancoli's text is used and those topics requiring trigonometry are omitted. It turns out that aside from the third chapter, where vector operations in two dimensions and projectile motion are the topics, only about 10% of the problems in the book require trigonometry.

However, three difficulties remained. First, there are too few algebra based problems in the text and they are not developed in a clear progression from simple to difficult. The assumption seems to be that all physics students are already very good at algebra. While that is certainly not true for our 9th graders, it is also probably not true in general: posing an obstacle to any student using this book. Second, there are not enough complex interesting problems that solely use algebra. Since an important aspect of this course is the social constructivist group work, challenging problems are required. Third, the book is written at too high a reading level: it is difficult for students to understand a topic by reading the book. Once again, this is clearly a problem for our 9th graders, but probably poses a problem for many students: simpler clearer language would help any reader.

The first difficulty was addressed by heavily supplementing the book with sets of problems that can be completed prior to attempting those in the text. The difficulty level of these supplementary problems progressively increases until it matches the problems in the text, at which point the text problems are used.

The second difficulty was addressed by supplementing the book with a set of more challenging algebra-based problems. These are problems that students can solve together while working in groups. The combination of the easier problems, the text problems and the more challenging problems allows students to work in their zone of proximal development a great part of each class.

The third difficulty was initially addressed by careful explanation in class. However, over the course of time the explanations that have been offered in class are also being recorded as written explanations that can serve as a supplementary reading on the topic. Further, by combining some of the supplementary problems, discussed above, to those written explanations complete chapters are being created based on the unique approach taken in this course. Four chapters are approaching completion and are already being used in class. The text of the chapters was written by me while the problems were written by my colleague, Yuriy Zavorotniy and edited by me. These chapters are on the topics of dynamics, energy, momentum and electric force and represent about 30% of the course.

Studying the text of those chapters will do more than any explanation that can be offered as to the nature of this course. Students who have been in the class and read the chapters agree that the class experience is very consistent between the two. So reading these chapters should give the reader an understanding of the setting in which algebra and physics are taught in a manner to support one another.

One aspect that needs to be noted is that in each example problem all the algebra steps are shown and explained. This is rarely the case in most textbooks and leads to much confusion on the part of students who do not want to admit that they do not understand how progress was made from one step to the next. The only way to support the development of the mediational tools involved in understanding both physics and algebra is to use them extensively in a context where they are useful and have meaning. That is the aim of the course, and naturally, the text that is being written to support it.

Analysis of *the Physics Text*

The text reflects the approach that has been developed to teach sophisticated mathematically intensive physics to 9th grade students who either just recently took, or who are in parallel taking, an algebra course. Trigonometry is not used in the course even though some students in the school have limited familiarity with it. What would be gained by adding trigonometry is more than offset by what would be lost: the need to track students based on this criterion and the distraction from developing better algebra skills in all students: algebra being the subject that is most used and most prone to misuse in later science and mathematics study.

The text is specifically geared to teaching algebra within the context of physics. The time is taken to introduce the necessary algebra to do the problems at hand. Although it may be the case that some students have already learned the needed algebra: it is probably not the case that they have a deep appreciation for its usefulness. Embedding the algebra topic at hand within a context benefits students regardless of their prior mathematics achievement.

An obvious example of this is solving literal equations, equations that are to be solved for symbols before values have been substituted. If a student understands how to solve the equation, $4x = 8$, for x, then they should know how to solve $m = \rho V$ for V: the same principle applies. This step from procedural to conceptual (or structural) mathematics is important if students are to become fluent in their understanding of mathematics. However, many students have simply memorized that you solve the first equation by dividing both sides by 4 and do not have a clue that you solve the second equation by dividing both sides by m. In the text, equations are solved for the unknown before values are substituted in and, especially in the early chapters, every step in that process is explicitly shown and explained.

After working with symbols, that approach is also applied to working with units: when values are substituted into the solved equation, those values include both numbers and units. Solving for the units extends the conceptual understanding of algebra.

While solving linear equations is required, and therefore taught, in the first chapters; studying collisions requires solving systems of linear equations. So, after students have become adept at solving linear equations in the first chapters; that knowledge is extended to systems of linear equations in the momentum chapter. This mathematical progression is embedded as a parallel track throughout the text.

Another example of this progression is seen in the use of scientific notation. In the first few chapters, scientific notation is avoided; all the numbers are kept whole and simple; the students are challenged enough with solving literal equations, often for the first time. The numbers themselves become more complex as the book progresses: students progress along parallel paths in terms of the sophistication of their understanding of both mathematics and physics. When the chapter on gravity is reached, scientific notation must be used: there is simply no other way to deal with the equation $F_G = GMm/r^2$; where $G = 6.7 \times 10^{-11}$ $N \cdot m^2/kg^2$ and masses have values as large as that of the sun, 2.0×10^{30} kg, without using scientific notation.

So a quick review (or introduction for some students) of scientific notation is done; reading and problems are worked on and assigned from an algebra text; and physics problems are done with escalating levels of difficulty. In the process of doing this all the rules concerning exponents are explored; why $10^3 \times 10^{-11} = 10^{-8}$; why $10^3 / 10^{-11} = 10^{14}$; why $10^3 \times 10^{-3} = 0$; why $10^0 = 1$; and why $x^0 = 1$. These are not just memorized; they are worked with and learned by the students; the students construct a deep understanding of why exponents work the way that they do; and they do that in a context where they see why this must be learned; it is simply the only way to solve problems involving gravity; to find that that the gravitational field of the earth, g, is 9.8 N/kg; to see how that relates to the orbit of the moon.

Once established in this context, problems for the remainder of the year often use scientific notation. This is fundamental to the nature of the course and the text: as students progress through the physics book they are also progressing through a mathematics text. Mathematical concepts are introduced one at a time so students get to use them extensively before proceeding. Once learned, concepts are used from then on: a layering of mathematical sophistication is embedded in the text.

When they get to Coulomb's Law a few months later, scientific notation is once again required; but now for very small charges not for very large masses and for the very large constant, $k = 9.0 \times 10^9$ N·m^2/C^2, not for the very small constant, $G = 6.7 \times 10^{-11}$ N·m^2/kg^2. In this context, students see the value of developing the nomenclature of milli (m): micro (μ): nano (n): and pico (p): they simply make it easier to work with small numbers. They could have memorized those at the start of the course, but that would have served little purpose: now when they are essential, they are taught and used.

The textbook is written in a conversational tone and does not, implicitly or explicitly, confront student beliefs: it does not say that what students believe about the world is wrong. Because of course, student beliefs are not wrong: within the context in which they live and in which we evolved those beliefs are perfectly useful and reasonable. So the book starts with those beliefs, and the p-prims which constitute them, and explains how they can be extended to be of use in new contexts.

For instance, humans intuitively believe that things that are equal and opposite cancel out: the p-prim for balance. That is used when developing the notion of free body diagrams and discussing net forces: the idea that two equal and oppositely directed forces add to zero. It is not necessary to prove that to students: they accept it without explanation, so we use it. Another example is the Container Schema (Lakoff & Nunez, 2000), also know as the Law of the

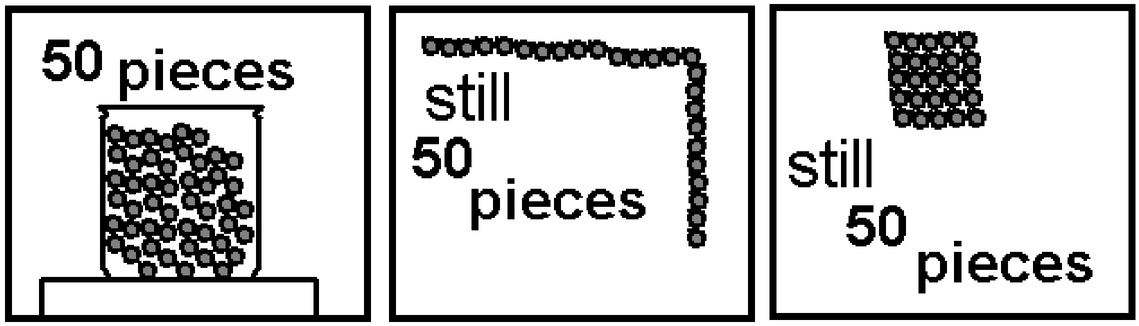
Excluded Middle: the idea that all objects are either inside or outside any given container. That is core of all the conservation laws and is accepted by students without proof, so it is part of the foundation that can be built upon. That is the key principle upon which the energy chapter, for instance is constructed.

While it is very difficult to compare textbooks in limited space: I will give it a try. I will do this by copying the explanations given for energy and work in the new text as well as those same sections from Co*nceptual Physics (Hewitt, 2002)* and *Physics: Principles and Applications (Giancoli, 1998)*.

Energy Chapter

Some of the most powerful tools in physics are based on **conservation principles**. The idea behind a conservation principle is that there are some properties of systems that don't change, even though other things about the system may.

For instance, let's say that I have a package of candy that contains exactly 50 pieces. If I take those pieces of candy out of the package and put them on top of a table, I still have 50 pieces. If I lay them end-to-end or arrange them into a rectangle, I still have 50 pieces. No matter how many different ways I arrange them; I still have 50 pieces. They may look different in each case, but the total number stays the same. In this example, I could say that the number of pieces of candy is conserved.



Energy is another example of a conserved property of a system. It's hard to come up with a meaningful definition of energy. It's a basic property of the universe, like time and space, so it's very hard to define. It's a lot easier to visualize a piece of candy than a piece of energy. However, it is possible to mathematically describe the various forms of energy. Having done that, it has consistently proven true that if you add up all the types and amounts of energy within a **closed system** the total amount of energy does not change.

To work with this definition it's important to understand the idea of a closed system. It's true that I could change the number of pieces of candy on the table by eating some of them, dropping a piece on the floor or by opening another package and spilling some of that new candy onto the table. We have to account for any candy that's been added to or taken away from the amount that we started with or we'll see that the number has changed and our conservation principle will seem to have been violated.

The same thing is true for energy. The amount of energy in a **closed system** stays constant. But that means that if we add energy to the system or take energy away from a system, we have to account for it. Unless we do that successfully, it will appear that the **Conservation of Energy principle** has been violated. One way that we can move energy into or out of a system is called **Work**. Work has a very specific mathematical definition in physics and it represents the movement of mechanical energy into or out of a system. If work is the only means to move energy into or out of our system than it will be true that

Initial Amount of Energy + Work = Final Amount of Energy

Or

$$\mathbf{E_0 + W = E_f}$$

The forms that energy takes can vary quite widely. Some of these forms include gravitational, electrical, chemical, kinetic, magnetic, elastic and nuclear; but there are many more. In this chapter, we'll be discussing several mechanical forms of energy, **kinetic energy**, **gravitational potential energy** and **elastic potential energy**, along with the concept of **work**.

Work

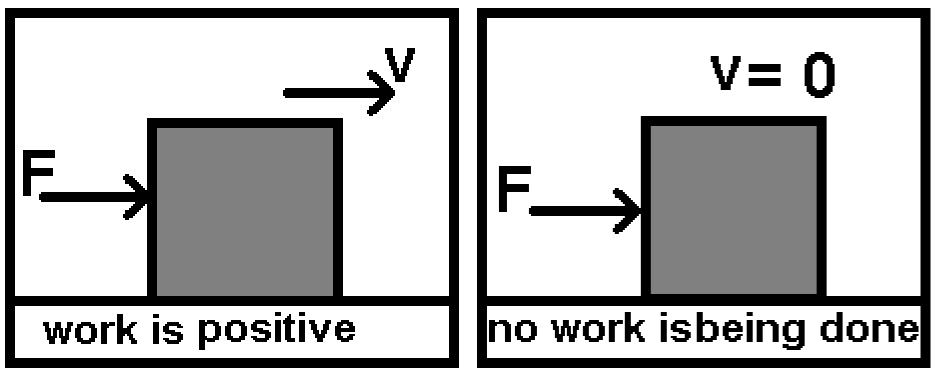
Work is defined as the product of the force applied to an object and the distance that the object moves in the direction of that force. The mathematical description of that definition is:

$$\mathbf{Work = Force \times Distance_{parallel}}$$

Or

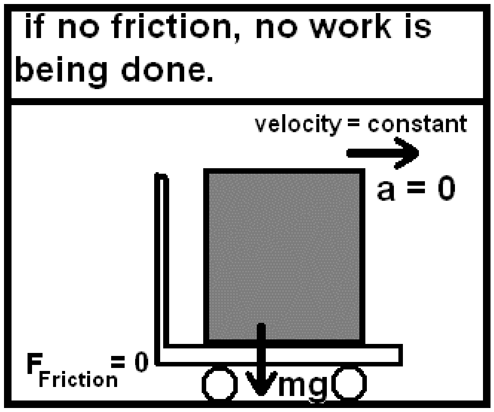
$$\mathbf{W = Fd}_{\text{parallel}}$$

It is important to note that work is proportional to the product of the force and the distance that the object moves **parallel to that force**. That means that if the object moves in the direction that I am pushing or pulling it, then I am doing work. If it does not move, or if it moves perpendicular to the direction that I am pushing or pulling it, I am not doing any work.

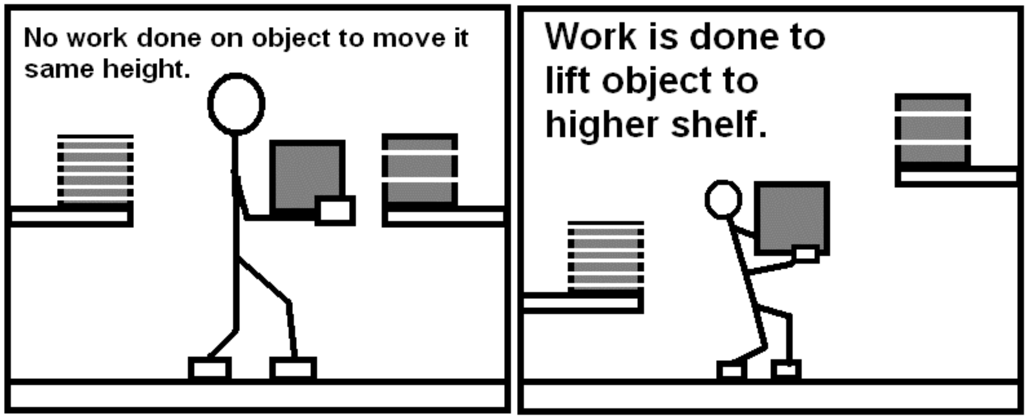


This can be confusing because the use of the word "work" in English is similar to but not the same as its use in physics. For instance if someone were to pay me to hold a heavy box up in the air while they move a table to sweep underneath it, I would say that I am doing work. But I would not be doing work according to the physics definition of the term. That is because the box is not moving in the direction of the force that I am applying. I am applying a force upwards but the box is stationary. Since d_{parallel} is equal to zero, so is the amount of work, W.

The same thing applies if I were to put that heavy box on a perfectly frictionless cart and push it to the side of the room at a constant velocity. Since the velocity is constant, the acceleration is zero. If there's no friction to overcome, then the force I need to apply (once I've gotten it moving) is zero. No force… no work.



The last way that I can do no work, according to the physics definition of work, is if I were to carry that box across the room at a constant velocity and put it on a shelf at the same height. Once again, I don't need to apply a horizontal force to keep moving at a constant velocity so there are no forces in the horizontal direction. I am applying a force in the vertical direction, to keep the box from falling to the ground. But the box is not moving in the vertical direction, it's moving in the horizontal direction. So in the horizontal direction, the force is equal to zero and in the vertical direction $d_{parallel}$ equals zero. The result is that W = 0 in both cases.



While our definition of work may not always seem to relate to our experience, it turns out to be a very useful tool in developing a theory of energy. In fact, the three forms of energy that we will be discussing in this chapter all become clear through thinking about them with respect to work.

Units of Energy

The unit of energy can be derived from the basic equation of work.

$W = F \times d_{parallel}$

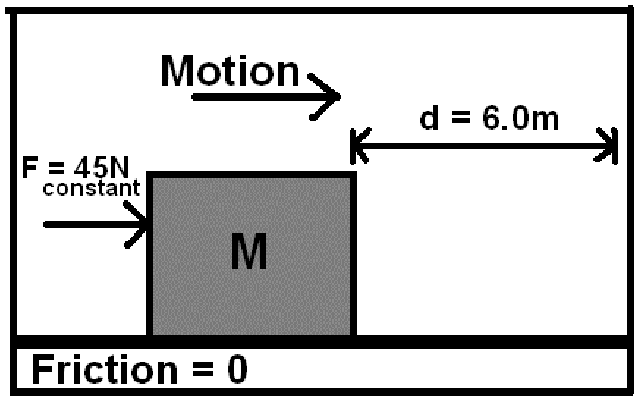
The SI units of force are Newtons (N) and of distance are meters (m). Therefore, the units of energy are Newton-meters (N-m). Out of respect for James Prescott Joule (1818-1889), a key formulator of the concept of energy, this is also referred to as a Joule (J).

$J = N\text{-}m$

$J = (kg\text{–}m / s^2) - m$

$\mathbf{J = N\text{-}m = kg\text{-}m^2 / s^2}$

Example 1: A constant force of 45 N is applied to an object on a frictionless surface. The force is applied in the same direction as the *motion of the object. How much work does that force do over a distance of 6.0m?*



Since the force and the distance that the object moves are parallel to one another the work done by the force will simply be the product of the two.

$W = Fd_{parallel}$

$= 45\ N \times 6m$

$= 270\ N\text{-}m$

$= 270\ J$

Example 2: A net force of 45N keeps an object moving in circular motion at a constant speed on a horizontal frictionless surface. The circumference of the circle is 6.0m. How much work does that force do during one rotation?

The force needed to keep an object moving in a circle at a constant speed on a horizontal frictionless surface is directed towards the center of the circle. However, the velocity of the object is always tangent to the circle.

Therefore F and d are always perpendicular to one another. As a result, both $d_{parallel}$ and the work done by the force are equal to zero.

To illustrate how the math is explained in doing a more complex example, I'll jump ahead a few pages so you can see how that looks.

Example 6: Use conservation of energy to determine how high a ball will go if it leaves the ground going straight up with a velocity of 24 m/s.

$E_0 + W = E_f$

but W = 0 so

$E_0 = E_f$

the energy is either GPE or KE so

$KE_0 + GPE_0 = KE_f + GPE_f$

then substitute in the formulas for each

$\frac{1}{2} mv_0^2 + mgh_0 = \frac{1}{2} m(v_f)^2 + mgh_f$

but h_0 and v_f are both = 0 so

$\frac{1}{2} mv_0^2 = mgh_f$

divide both sides by m to cancel it out

$\frac{1}{2} v_0^2 = gh_f$

double both sides

$v_0^2 = 2(gh_f)$

divide both sides by 2 g

$h_f = v_0^2 / (2g)$

substitute in the given values

$h_f = (24\ m/s)^2 / ((2)(9.8\ m/s^2))$

$h_f = (576\ m^2/s^2) / (19.6\ m/s^2)$

$h_f = 29\ m$

Now let us look at how those same topics are explained in Giancoli's book. This is an excellent book, and we are using it in the course now; but it has to be heavily supplemented to become effective in achieving the objectives of the course. That is because it does not show all the algebraic steps in its examples; uses trigonometry in even the simplest problems; and introduces complicating and unnecessary facts and concepts: our 9th grade students do not need to know that the British units for energy is the foot-pound or that the cgs unit is the erg.

I also do not think that this text gets across the very conceptual nature of energy; that energy is a human construct; nor does it make the topic very accessible. Instead, it plunges the student into relatively complicated examples using trigonometry where it really does not add much. That might be alright with an advanced student who will understand it anyway; but I am not sure if it really helps any student. The more complicated mathematics could be developed as the chapter goes along rather than in the first explanation.

A roller coaster at the highest point of its journey has its maximum potential energy (PE). As it rolls downhill, it loses PE and gains in kinetic energy (KE). Total energy is conserved. So if there is no friction, the loss in PE equals the gain in KE. If there is friction, the loss in PE equals the gain in KE plus the thermal energy produced by the work done by friction.

CHAPTER 6

WORK AND ENERGY

Until now we have been studying the motion of an object in terms of Newton's three laws of motion. In that analysis, *force* played a central role as the quantity determining the motion. In this chapter and the next, we discuss an alternative analysis of the motion of an object in terms of the quantities *energy* and *momentum*. The importance of these quantities is that they are *conserved*. That is, in quite general circumstances they remain constant. That conserved quantities exist not only gives us a deeper insight into the nature of the world, but also gives us another way to approach practical problems. We still consider only translational motion, without rotation, in this chapter.

The conservation laws of energy and momentum are especially valuable in dealing with systems of many objects in which a detailed consideration of the forces involved would be difficult.

This chapter is devoted to the very important concept of *energy* and the closely related concept of *work*, which are scalar quantities and thus have no direction associated with them. Since these two quantities are scalars, they are often easier to deal with than are vector quantities such as force and acceleration. Energy derives its importance from two sources. First, it is a conserved quantity. Second, energy is a concept that is useful not only in the study of motion, but in all areas of physics and other sciences as well. But before discussing energy itself, we first examine the concept of work.

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6–1 Work Done by a Constant Force

The word *work* has a variety of meanings in everyday language. But in physics, work is given a very specific meaning to describe what is accomplished by the action of a force when it acts on an object as the object moves through a distance. Specifically, the **work** done on an object by a constant force (constant in both magnitude and direction) is defined to be *the product of the magnitude of the displacement times the component of the force parallel to the displacement.* In equation form, we can write

$$W = F_{\parallel}d$$

where $F_{\parallel}$ is the component of the constant force **F** parallel to the displacement **d**. We can also write

Work defined

$$W = Fd\cos\theta, \tag{6–1}$$

where F is the magnitude of the constant force, d is the magnitude of the displacement of the object, and θ is the angle between the directions of the force and the displacement. The $\cos\theta$ factor appears in Eq. 6–1 because $F\cos\theta\ (=F_{\parallel})$ is the component of **F** parallel to **d** (Fig. 6–1). Work is a scalar quantity—it has only magnitude.

Let's first consider the case in which the motion and the force are in the same direction, so $\theta = 0$ and $\cos\theta = 1$, and then $W = Fd$. For example, if you push a loaded grocery cart a distance of 50 m by exerting a horizontal force of 30 N on the cart, you do $30\text{ N} \times 50\text{ m} = 1500\text{ N}\cdot\text{m}$ of work on the cart.

Units for work: the joule

As this example shows, in SI units, work is measured in newton-meters. A special name is given to this unit, the **joule** (J): $1\text{ J} = 1\text{ N}\cdot\text{m}$. In the cgs system, the unit of work is called the *erg* and is defined as $1\text{ erg} = 1\text{ dyne}\cdot\text{cm}$. In British units, work is measured in foot-pounds. It is easy to show that $1\text{ J} = 10^7\text{ erg} = 0.7376\text{ ft}\cdot\text{lb}$.

Force without work

A force can be exerted on an object and yet do no work. For example, if you hold a heavy bag of groceries in your hands at rest, you do no work on it. A force is exerted, but the displacement is zero, so the work $W = 0$. You also do no work on the bag of groceries if you carry it as you walk

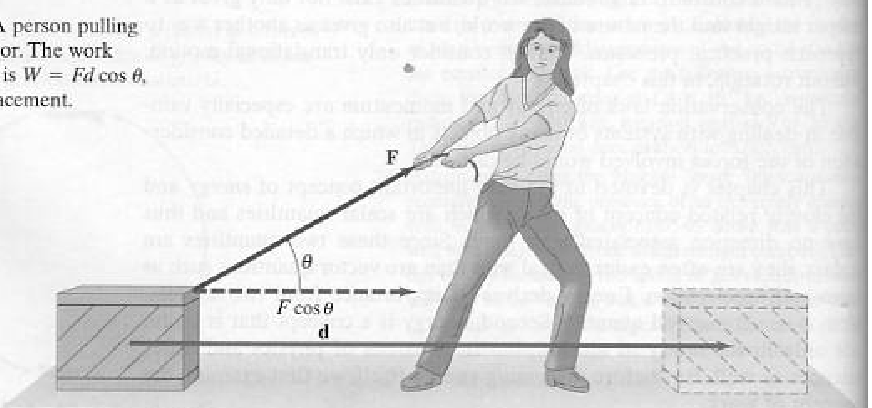

FIGURE 6–1 A person pulling a crate along the floor. The work done by the force **F** is $W = Fd\cos\theta$, where **d** is the displacement.

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horizontally across the floor at constant velocity, as shown in Fig. 6–2. No horizontal force is required to move the package at a constant velocity. However, you do exert an upward force **F** on the package equal to its weight. But this upward force is perpendicular to the horizontal motion of the package and thus has nothing to do with that motion. Hence, the upward force is doing no work. This conclusion comes from our definition of work, Eq. 6–1: $W = 0$, because $\theta = 90°$ and $\cos 90° = 0$. Thus, when a particular force is perpendicular to the motion, no work is done by that force. (When you start or stop walking, there is a horizontal acceleration and you do briefly exert a horizontal force, and thus do work.)

When dealing with work, as with force, it is necessary to specify whether you are talking about work done *by* a specific object or done *on* a specific object. It is also important to specify whether the work done is due to one particular force (and which one), or work done by the total *net force* on the object.

FIGURE 6–2 Work done on the bag of groceries in this case is zero since **F** is perpendicular to the displacement **d**.

EXAMPLE 6–1 **Work done on a crate.** A 50-kg crate is pulled 40 m along a horizontal floor by a constant force exerted by a person, $F_P = 100\,\text{N}$, which acts at a 37° angle as shown in Fig. 6–3. The floor is rough and exerts a friction force $F_{fr} = 50\,\text{N}$. Determine the work done by each force acting on the crate, and the net work done on the crate.

SOLUTION We choose our coordinate system so that **x** can be the vector that represents the 40-m displacement (that is, along the x axis). There are four forces acting on the crate, as shown in Fig. 6–3: the force exerted by the person $\mathbf{F}_P$; the friction force $\mathbf{F}_{fr}$; the crate's weight $m\mathbf{g}$; and the normal force $\mathbf{F}_N$ exerted upward by the floor. The work done by the gravitational and normal forces is zero, since they are perpendicular to the displacement **x** ($\theta = 90°$ in Eq. 6–1):

$$W_G = mgx \cos 90° = 0$$

$$W_N = F_N x \cos 90° = 0.$$

The work done by $\mathbf{F}_P$ is

$$W_P = F_P x \cos\theta = (100\,\text{N})(40\,\text{m}) \cos 37° = 3200\,\text{J}.$$

The work done by the friction force is

$$\begin{aligned} W_{fr} &= F_{fr} x \cos 180° \\ &= (50\,\text{N})(40\,\text{m})(-1) = -2000\,\text{J}. \end{aligned}$$

The angle between the displacement **x** and $\mathbf{F}_{fr}$ is 180° because they point in opposite directions. Since the force of friction is opposing the motion, it does *negative* work on the crate.

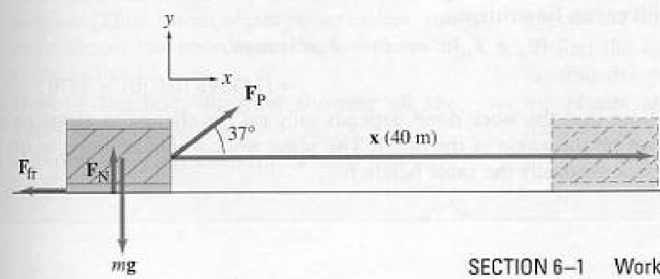

FIGURE 6–3 Example 6–1: 50-kg crate being pulled along a floor.

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W_{net} is the work done by all the forces acting on the body

Finally, the net work can be calculated in two equivalent ways. (1) The net work done on an object is the algebraic sum of the work done by each force, since work is a scalar:

$$W_{net} = W_G + W_N + W_P + W_{fr}$$
$$= 0 + 0 + 3200\ \text{J} - 2000\ \text{J} = 1200\ \text{J}.$$

(2) The net work can also be calculated by first determining the net force on the object and then taking its component along the displacement: $(F_{net})_x = F_P \cos\theta - F_{fr}$. Then the net work is

$$W_{net} = (F_{net})_x x = (F_P \cos\theta - F_{fr})x$$
$$= (100\ \text{N} \cos 37° - 50\ \text{N})(40\ \text{m}) = 1200\ \text{J}.$$

In the vertical (y) direction, there is no displacement and no work done.

Negative work

In Example 6–1 we saw that friction did negative work. In general, the work done by a force is negative whenever the force (or the component of the force, $F_{\parallel}$) acts in the direction opposite to the direction of motion.

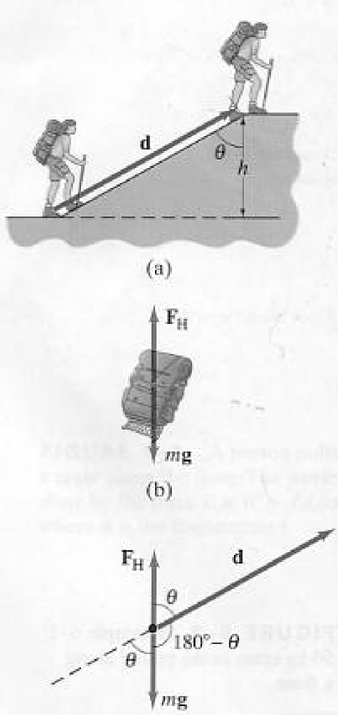

FIGURE 6–4 Example 6–2.

EXAMPLE 6–2 **Work on a backpack.** (*a*) Determine the work a hiker must do on a 15.0-kg backpack to carry it up a hill of height $h = 10.0$ m, as shown in Fig. 6–4a. Determine also (*b*) the work done by gravity on the backpack, and (*c*) the net work done on the backpack. For simplicity, assume the motion is smooth and at constant velocity (i.e., there is negligible acceleration).

SOLUTION (*a*) The forces on the backpack are shown in Fig. 6–4b: the force of gravity, $m\mathbf{g}$, acting downward; and $\mathbf{F}_H$, the force the hiker must exert upward to support the pack. Since we assume there is negligible acceleration, horizontal forces are negligible. In the vertical (y) direction, we choose up as positive. Newton's second law applied to the backpack gives

$$\Sigma F_y = ma_y$$
$$F_H - mg = 0.$$

Hence,

$$F_H = mg = (15.0\ \text{kg})(9.80\ \text{m/s}^2) = 147\ \text{N}.$$

To calculate the work done by the hiker on the backpack, Eq. 6–1 can be written

$$W_H = F_H(d \cos\theta),$$

and we note from Fig. 6–4a that $d\cos\theta = h$. So the work done by the hiker can be written:

$$W_H = F_H(d\ \cos\theta) = F_H h = mgh$$
$$= (147\ \text{N})(10.0\ \text{m}) = 1470\ \text{J}.$$

Note that the work done depends only on the change in elevation and not on the angle of the hill, θ. The same work would be done to lift the pack vertically the same height h.

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(*b*) The work done by gravity is (from Eq. 6–1 and Fig. 6–4c):

$$W_G = (F_G)(d)\cos(180^\circ - \theta).$$

Since $\cos(180^\circ - \theta) = -\cos\theta$, we have

$$\begin{aligned} W_G = (F_G)(d)(-\cos\theta) &= mg(-d\cos\theta) \\ &= -mgh \\ &= -(15.0\ \text{kg})(9.80\ \text{m/s}^2)(10.0\ \text{m}) = -1470\ \text{J}. \end{aligned}$$

Note that the work done by gravity doesn't depend on the angle of the incline but only on the vertical height h of the hill. This is because gravity does work only in the vertical direction. We will make use of this important result later.

Work done by gravity depends on the height of the hill and not on the angle of incline

(*c*) The *net* work done on the backpack is $W_{net} = 0$, since the net force on the backpack is zero (it is assumed not to accelerate significantly). We can also determine the net work done by writing

$$W_{net} = W_G + W_H = -1470\ \text{J} + 1470\ \text{J} = 0$$

which is, as it should be, the same result.

Note in this example that even though the *net* work on the backpack is zero, the hiker nonetheless does do work on the backpack equal to 1470 J.

Hiker does work on pack, but the net work = 0

CONCEPTUAL EXAMPLE 6–3 **Does Earth do work on the Moon?** The Moon revolves around the Earth in a circular orbit, kept there by the gravitational force exerted by the Earth. Does gravity do (*a*) positive work, (*b*) negative work, or (*c*) no work at all on the Moon?

RESPONSE The gravitational force on the Moon (Fig. 6–5) acts toward the Earth (as a centripetal force), inward along the radius of the Moon's orbit. The Moon's displacement at any moment is along the circle, in the direction of its velocity, perpendicular to the radius and perpendicular to the force of gravity. Hence the angle θ between the force and the instantaneous displacement of the Moon is 90°, and the work done by gravity is therefore zero ($\cos 90^\circ = 0$).

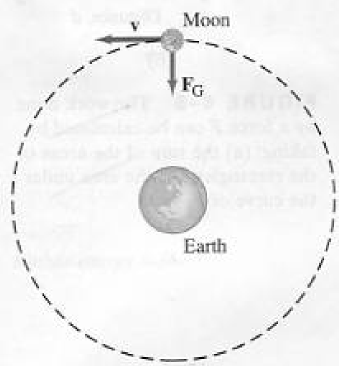

FIGURE 6–5
Conceptual Example 6–3.

➡ PROBLEM SOLVING Work

1. Choose an *xy* coordinate system. If the body is in motion, it may be convenient to choose the direction of motion as one of the coordinate directions. [Thus, for an object on an incline, you might choose one coordinate axis to be parallel to the incline.]
2. Draw a free-body diagram showing all the forces acting on the body.
3. Determine any unknown forces using Newton's laws.
4. Find the work done *by* a specific force *on* the body by using $W = Fd\cos\theta$. Note that the work done is negative when a force tends to oppose the displacement.
5. To find the *net* work done on the body, either (a) find the work done by each force and add the results algebraically; or (b) find the net force on the object, F_{net}, and then use it to find the net work done:
$$W_{net} = F_{net}\, d\cos\theta.$$

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Now, let us look at how Hewitt treats those same topics in *Conceptual Physics (2002)*. The following pages include all the worked out examples in the energy chapter: none. This text is dedicated to developing the ideas of physics with very minimal mathematics. While some mathematical problems occur at the end of chapters, they are not explained in the text through examples. In this case, the idea of explaining energy without mathematics seems strange since energy is a mathematical construct: there is no such thing as “energy” without the mathematics that defines it.

While the belief seems to be that in the absence of problems students will focus on ideas, my experience with students using this book does not support that. In the absence of problems: students memorize terms. They can regurgitate the definition of work or energy, but they don’t develop a feeling for what they are or how to use them.

Of course, this also means that there is no attempt made to embed mathematics in the context of physics. Problem solving is necessary if a student is to appreciate and understand physics and using mathematics in physics is a great way to deepen a student’s understanding of mathematics.

> Understanding is supported best through a delicate balance among engaged students in solving challenging problems, examining increasingly better solution methods, and providing information for students at just the right times (Dewey 1933; Brownell and Sims 1946; Hiebert et al. 1997) (Hiebert & Wearne, 2003, p. 5)

This book takes a completely different path and, in the end, both the teachers and students felt that this text did not encourage learning so much as memorization. In AY2006, we began using the Giancoli text even in our regular, non-honors, 9^{th} grade physics classes. However, we needed to supplement it heavily to make it more useful and accessible to all our students. As the chapters have been written for the new text, they have been copied and given out to the classes in lieu of the supplementary materials and that seems to work better.

Chapter 8

Energy

The mechanical energy of the wind can be harnessed to produce electrical power.

Energy is the most central concept underlying all of science. Surprisingly, the idea of energy was unknown to Isaac Newton, and its existence was still being debated in the 1850s. Even though the concept of energy is relatively new, today we find it ingrained not only in all branches of science, but in nearly every aspect of human society. We are all quite familiar with energy. Energy comes to us from the sun in the form of sunlight, it is in the food we eat, and it sustains life. Energy may be the most familiar concept in science, yet it is one of the most difficult to define. Persons, places, and things have energy, but we observe only the effects of energy when something is happening—only when energy is being transferred from one place to another or transformed from one form to another. We begin our study of energy by observing a related concept, work.

8.1 Work

The previous chapter showed that the change in an object's motion is related to both force and how long the force acts. "How long" meant time. Remember, the quantity *force × time* is called *impulse.* But "how long" need not always mean time. It can mean distance also. When we consider the quantity *force × distance,* we are talking about an entirely different concept. This concept is called **work.**

We do work when we lift a load against Earth's gravity. The heavier the load or the higher we lift it, the more work we do. Two things enter into every case where work is done: (1) the *application of a force,* and (2) the *movement of something* by that force.

Let's look at the simplest case, in which the force is constant and the motion takes place in a straight line in the direction of the force.

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Figure 8.1 ▲
Work is done in lifting the barbell. If the barbell could be lifted twice as high, the weight lifter would have to do twice as much work.

Then the work done on an object by an applied force is the product of the force and the distance through which the object is moved.*

$$\text{work} = \text{force} \times \text{distance}$$

In equation form,

$$W = Fd$$

If we lift two loads up one story, we do twice as much work as we would in lifting one load the same distance, because the *force* needed to lift twice the weight is twice as great. Similarly, if we lift one load two stories instead of one story, we do twice as much work because the *distance* is twice as great.

Notice that the definition of work involves both a force *and* a distance. A weight lifter holding a barbell weighing 1000 N over his head does no work on the barbell. He may get really tired holding it, but if the barbell is not moved by the force he exerts, he does no work on the barbell. Work may be done on the muscles by stretching and squeezing them, which is force times distance on a biological scale, but this work is not done on the barbell. Lifting the barbell, however, is a different story. When the weight lifter raises the barbell from the floor, he is doing work on it.

Work generally falls into two categories. One of these is the work done against another force. When an archer stretches her bowstring, she is doing work against the elastic forces of the bow. Similarly, when the ram of a pile driver is raised, work is required to raise the ram against the force of gravity. When you do push-ups, you do work against your own weight. You do work on something when you force it to move against the influence of an opposing force—often friction.

The other category of work is work done to change the speed of an object. This kind of work is done in bringing an automobile up to speed or in slowing it down.

The unit of measurement for work combines a unit of force, N, with a unit of distance, m. The resulting unit of work is the newton-meter (N·m), also called the **joule** (rhymes with cool) in honor of James Joule. One joule (J) of work is done when a force of 1 N is exerted over a distance of 1 m, as in lifting an apple over your head. For larger values we speak of kilojoules (kJ)—thousands of joules—or megajoules (MJ)—millions of joules. The weight lifter in Figure 8.1 does work on the order of kilojoules. To stop a loaded truck going at 100 km/h takes megajoules of work.

8.2 Power

The definition of work says nothing about how long it takes to do the work. When carrying a load up some stairs, you do the same amount of work whether you walk or run up the stairs. So why are you more

1 *Explore* **2** *Develop* **3** *Apply*

3 **Problem-Solving Exercises in Physics** *5-1*

* For the more general case, work is the product of the *component* of force acting in the direction of motion and the distance moved.

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The 9th and 10th grade Physics Curricula

In this section the relationship between the curricula for the two physics courses is made clear, further addressing the second and third research questions. The 9th grade physics course serves as the foundation for the entire science and mathematics program. It supports all the science that is to follow as well as helping to establish a deeper understanding of mathematics. Because only a portion of the students will go on to study AP Physics B the following year; the course curriculum (see Appendix B) was written so that the course could serve two roles: it must describe the first half of a two-year sequence culminating in the AP Physics B exam and it must represent an effective one-year standalone physics course. While there are many ways to write a curriculum that serves either of these purposes, serving both of them acts as a constraint.

It was possible to write a curriculum that serves both purposes because there are many shared objectives. In order of priority, the goals for the course were to develop in students the following: problem solving strategies and analytical thinking; a deeper understanding of the power and usefulness of mathematics; an understanding of the nature of science; and physics content. Physics content is the least priority as it will be the first thing forgotten by students who go no further in physics: however, it is still important for those students who go on to more advanced courses that rely upon that content knowledge.

Based on these priorities, the course was developed to cover just two major topics: Mechanics and Electricity & Magnetism. In both cases, these topics would be explored carefully and to the level called for by the AP Physics B curriculum; the only exception to that being the use of trigonometry which would wait until the following year.

Within these two topics there is a plethora of complex and interesting problems: problems that serve as a context within which analytical skills, mathematical techniques and the skills of inquiry can be developed. Two other choices could have been made and its worth commenting on them to illustrate the different nature of the courses that would have resulted.

When the highest level 9^{th} grade physics course was Physics I, it was only taken by Pre-Engineering students; all of whom were required to take Physics II the following year; and some of whom then went on to study AP Physics B in 11^{th} grade. At that time, Physics I was devoted to Mechanics alone. All these students were studying geometry in parallel to physics and the geometry curriculum had been designed to teach all the trigonometric functions by mid-year. The physics course mirrored that by teaching mechanics without trigonometry during the first half of the year and introducing trigonometry during the second half.

When the decision was made to let students from other programs, not Pre-Engineering, take Physics Honors the curriculum had to change. First, those students were not necessarily taking geometry in 9^{th} grade so trigonometry could not be used in the second half of the year: this eliminated the teaching of trigonometry based mechanics. Second, those students were unlikely to go on to a second year physics course: this might be their only exposure to physics. If so, just studying mechanics did not seem sufficient. Third, it was felt that developing in all the students an understanding of the atom and electric force would be important to prepare them for chemistry. As a result, the decision was made to move trigonometry based mechanics to the beginning of the 10th grade course and devote the second half of the 9th grade course to Electricity and Magnetism. This made the course more diverse but still very much focused on problem solving, mathematics and inquiry.

An alternative direction would have been to make the course more of a survey course: the typical high school physics course that is taught in many schools and assessed by the Regents Physics exam and the Physics SAT II exam. However, this would have had the effect of emphasizing content over our goals for the course: problem solving, mathematics and inquiry. Courses of that nature cover twice the material in the same amount of time: the result is that depth and understanding is sacrificed for breadth.

If the primary goal of the course were to teach physics content, that would have been a reasonable decision. However, it is questionable how much of that content is retained and much must be sacrificed in order to cover it. As was pointed out by Van Heuvelen (2001), and cited above, when university physics majors were later surveyed as to what was most valuable of what they learned in the university; problem solving was ranked highest and physics content was ranked lowest. This would surely be even more true of high school students; the vast majority of whom will not become physics majors.

Having completed their Physics Honors course; students who choose to do so may take AP Physics B. While the curriculum for AP Physics B is established by the College Board: the curriculum for this course, of that same name, is unique (see appendix C). That is because of the way that the objectives of the College Board curriculum have been divided between the two years: that division fundamentally changes the nature of both courses: Physics Honors and AP Physics B.

The first topic of the AP Physics B combines the learning that was accomplished in two of the students' prior courses: the mechanics of Physics Honors is combined with the trigonometry of Geometry Honors. This combination is powerful: it allows students to solve all the two-dimensional mechanics problems that had been held in abeyance. It opens the door for them to analyze new classes of problems, like projectile motion; the motion of an electron through a cathode ray tube; or the net force due to three charges that do not lie on a line, as they were constrained from doing the prior year.

Rather than re-teach the prior year's content; that content serves as a foundation upon which is built an entirely new understanding; reinforcing the prior year's learning and showing students its usefulness. All the topics of the prior year are reprised by seeing them through this new prism of trigonometry. This becomes much more than a review; it is s rediscovery of the mathematics and physics that they learned before. This is followed by teaching students the remaining topics of the AP Physics B curriculum: waves; sound; wave optics; geometric optics; thermodynamics; and introductory atomic & nuclear physics.

Analysis of AP Results

This section answers the fourth research question, “How does the AP performance of the students in this program compare to that of students in other New Jersey schools?”. I evaluated the AP results in four ways. I determined the average score for those who took each test; the AP participation rate by dividing the total number of tests taken by the number of graduating seniors; the passing rate by dividing the number of scores of 3 or above by the number of graduating seniors; and a weighted measure of overall performance through the AP Metric: calculated by dividing the number of AP points earned by the number of graduating seniors. Below, I provide data for the school, its departments and the individual courses. I also calculate normalized results, for participation, passing rates and the AP Metric, by dividing the school’s results by that of the overall state. All data are provided from the inception of the school through AY2005, the last year for which AP scores have been received. The only exception is that pertaining to school participation: those data are available through AY2006.

A general picture of the progress of the school can be seen in Figure 13, Figure 14, and Figure 15. These figures show the number of AP exams taken each year and normalized comparisons of the school versus New Jersey using the passing rate on AP exams and the AP Metric (calculated for all possible AP courses, regardless if they are offered by the school). A reading of 1 would put the school on par with New Jersey: the AY2005 figures of 1.3 and 1.4 show that the school exceeded the New Jersey rate by 30% and 40% by these measures.

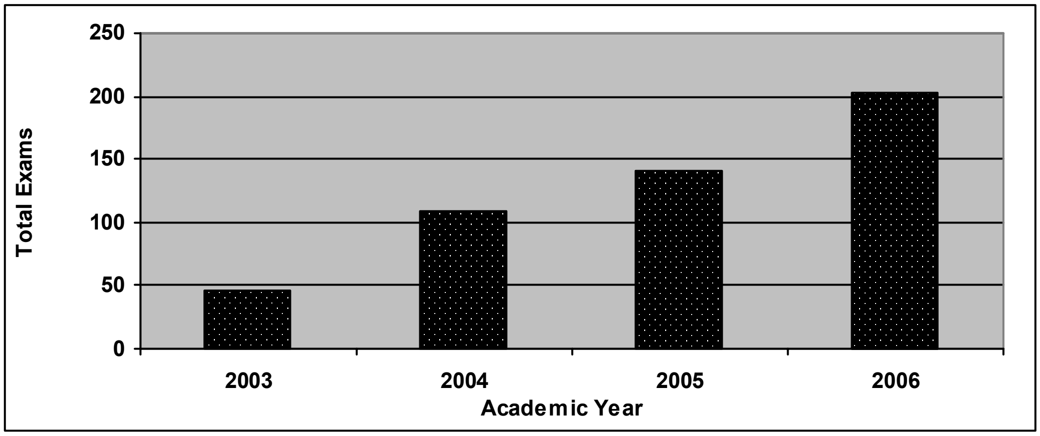

Figure 13: Schoolwide AP participation: the number of AP exams per year.

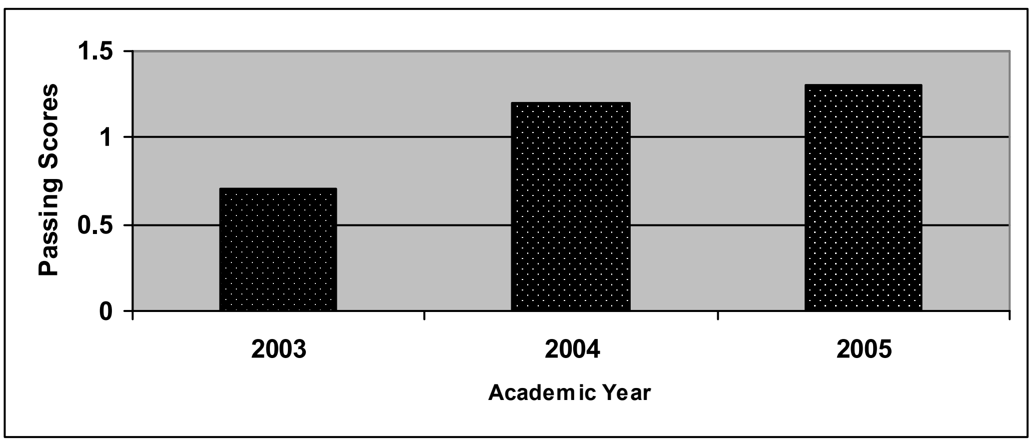

Figure 14: Normalized school performance based on number of AP passing scores (NJ=1)

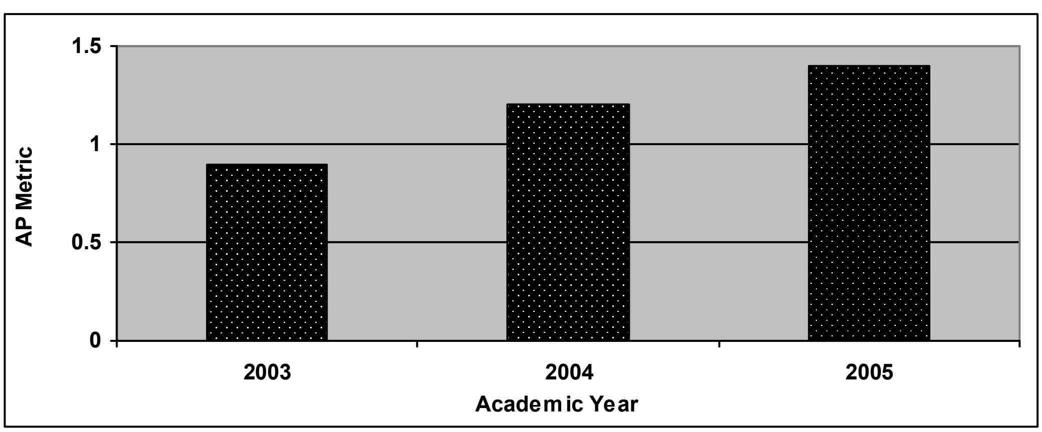

Figure 15: Normalized schoolwide performance as measured by the AP Metric (NJ =1)

The growth in these measures is mostly due to the rapid growth of AP participation at the school. Figure 16, Figure 17 and Figure 18 reveal that trend and break it down by department. As described above, departmental comparisons are important for this study as they make it possible to contrast the performance of departments which should be affected by the implementation of the new science sequence to those that should not.

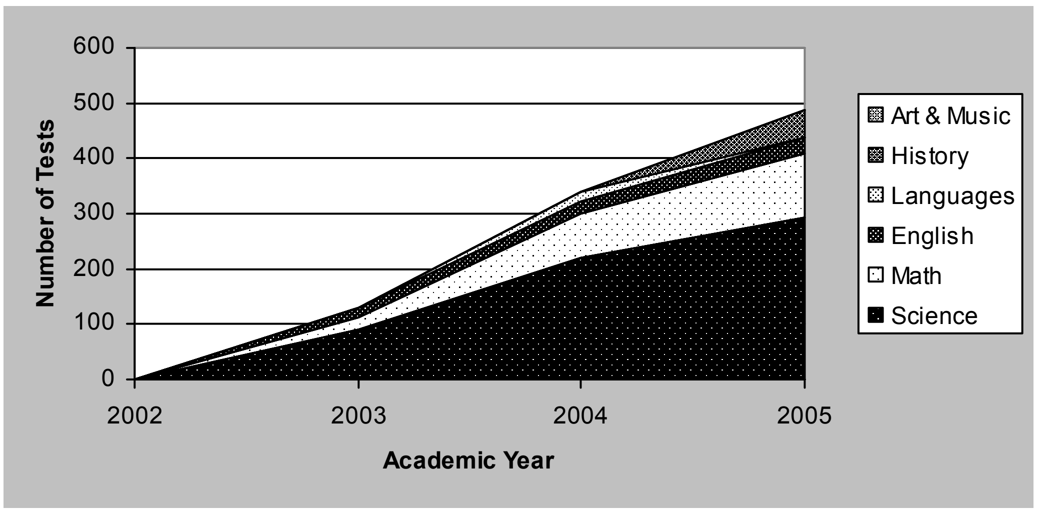

Figure 16: Total schoolwide AP points by department.

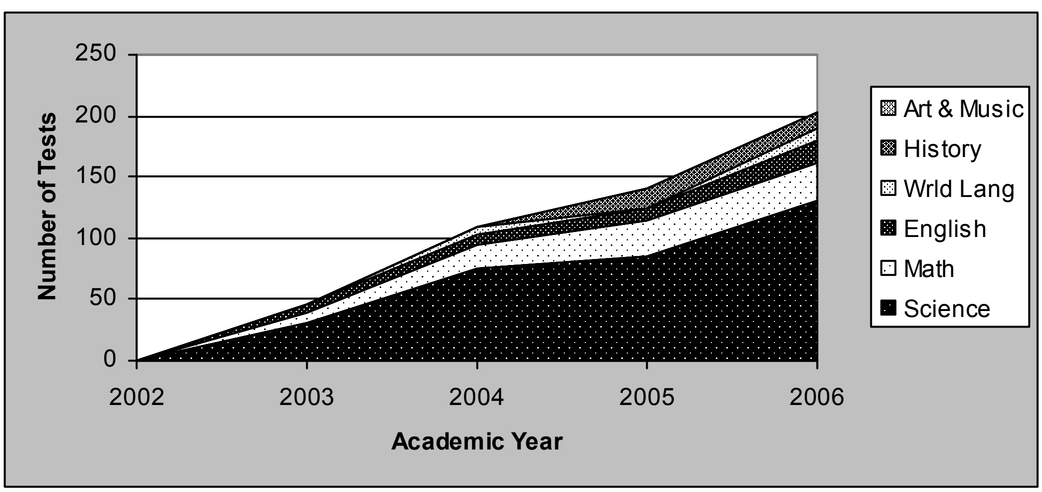

Figure 17: Total schoolwide AP exams by department.

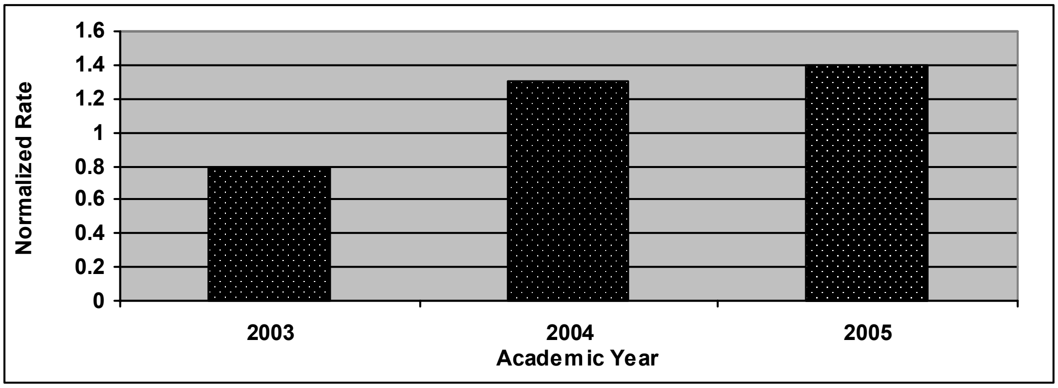

Figure 18: Normalized schoolwide AP participation (NJ Rate =1).

The above charts clearly show that the number of AP exams taken at the school has increased dramatically each year. Part of that is due to the growth in the size of the school from a graduating class of 82 seniors in 2003 to 150 students in AY2006. However, the normalized data given in Figure 18 shows the growth per student relative to New Jersey. This shows that from AY2003 to AY2005 the normalized participation rate grew from about 75% of the state average to about 140% of the state.

As this study is focusing on the effect of the science/math program it is important to look at the differential results between science and math versus the other departments in the school. As the students in the school perform comparably in terms of their math and verbal SAT results, any difference can be plausibly argued to be an effect of the program.

Figure **19** shows the raw number of AP exams taken by department while Figure 20 divides those figures by the number of graduating seniors in order to compensate for changes in enrollment.

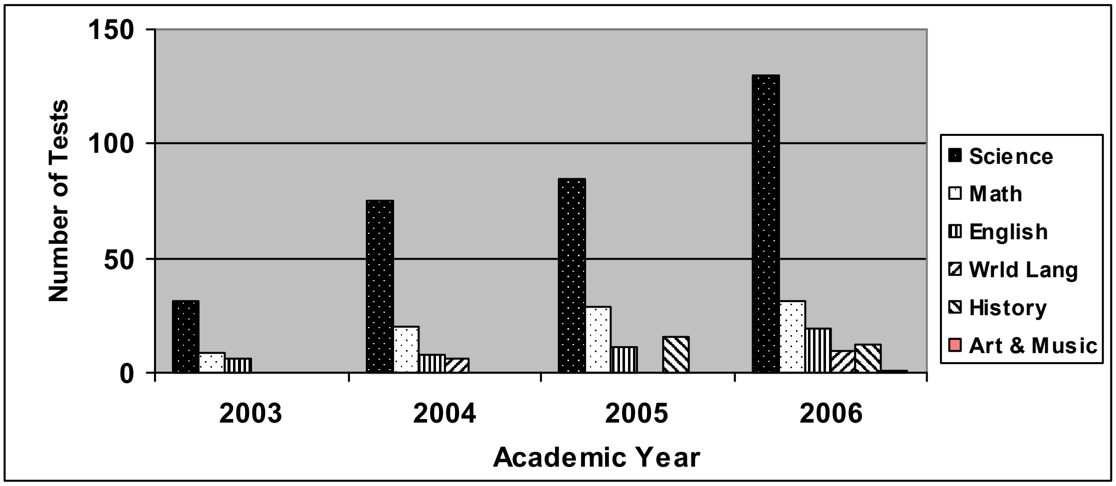

Figure 19: AP exams by department.

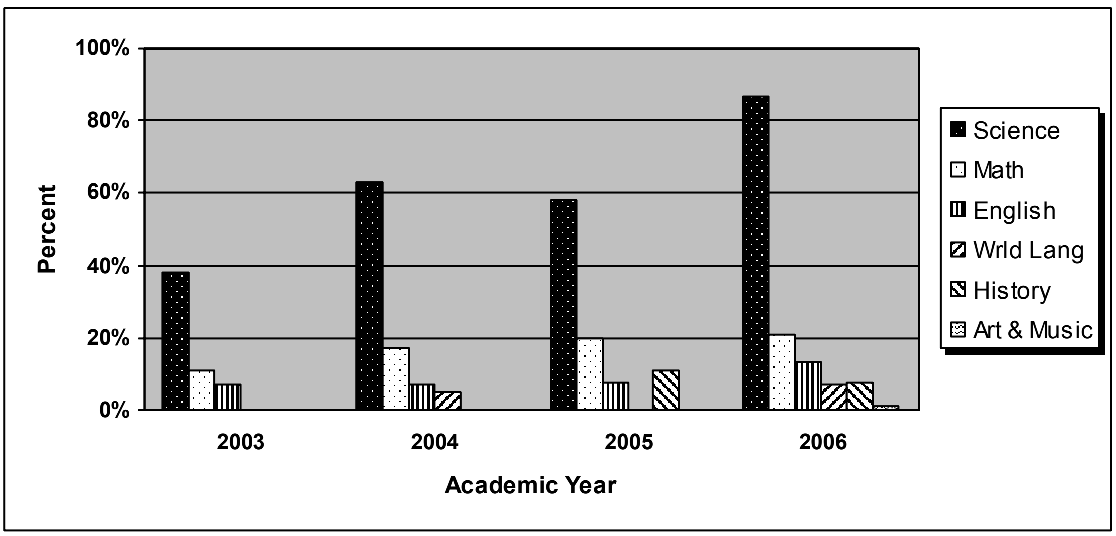

Figure 20: AP participation rate by department.

While the AP scores for AY2006 are not yet available, the number of number of passing scores by department though AY2005 is shown in Figure 21.

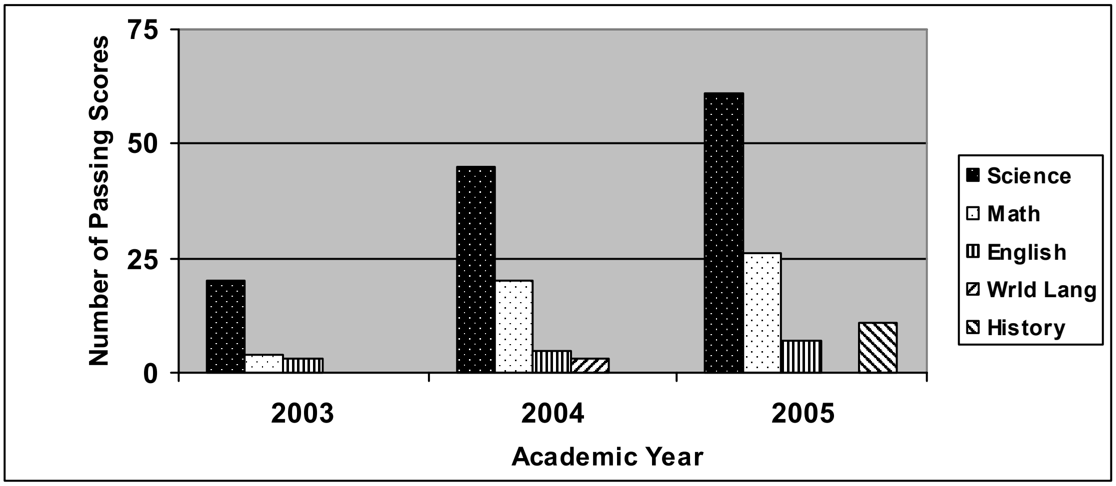

Figure 21: Number of AP Passing Scores by department.

In Figure 22, I normalized the school's departmental participation rates to that of the state to compensate for statewide variances. I did this by dividing the school participation rate by the state participation rate for each department: the result is a normalized comparison with 1 signifying that the school rate equals that of the state; numbers above 1 give the multiple of the school rate; and numbers below 1 indicate the fraction of the school rate. The 2006 figures are based on a combination of the actual school figures and projected state figures based on prior year participation rates, which have been relatively stable.

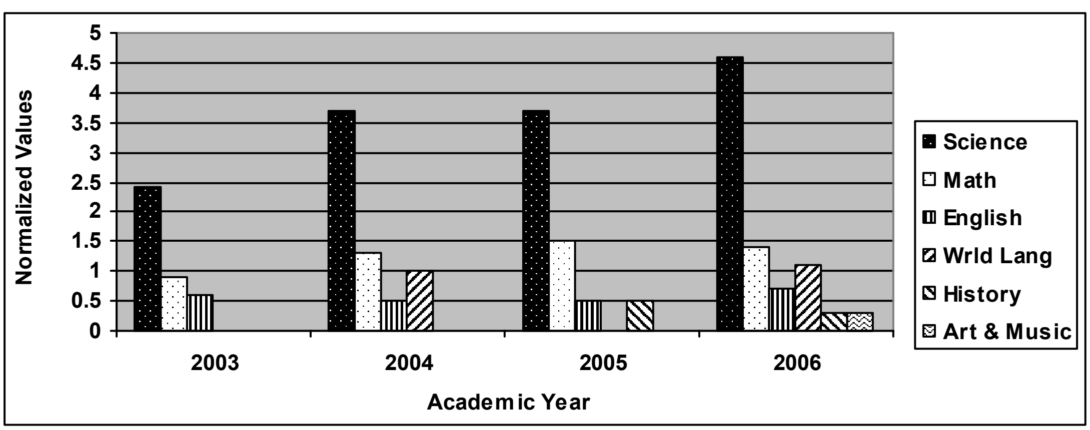

Figure 22: Normalized Departmental Participation Rate (NJ Rate =1)

The above charts (Figure 19, Figure 20, Figure 21 and Figure 22) make it clear that the high participation rate for the school is dominated by science. Figure 23 and Figure 24 show that, despite those high participation rates, the average scores on the exams have stayed relatively consistent and are in line with the state averages. It would have been easy to have raised the average score simply by restricting who took the AP exam, but that would not have been consistent with the goal of the program.

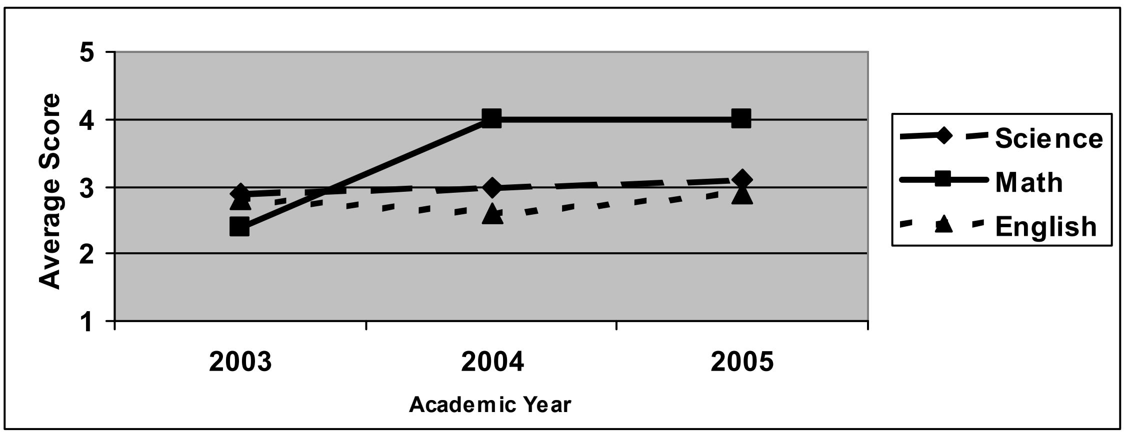

Figure 23: Average school AP scores by department.

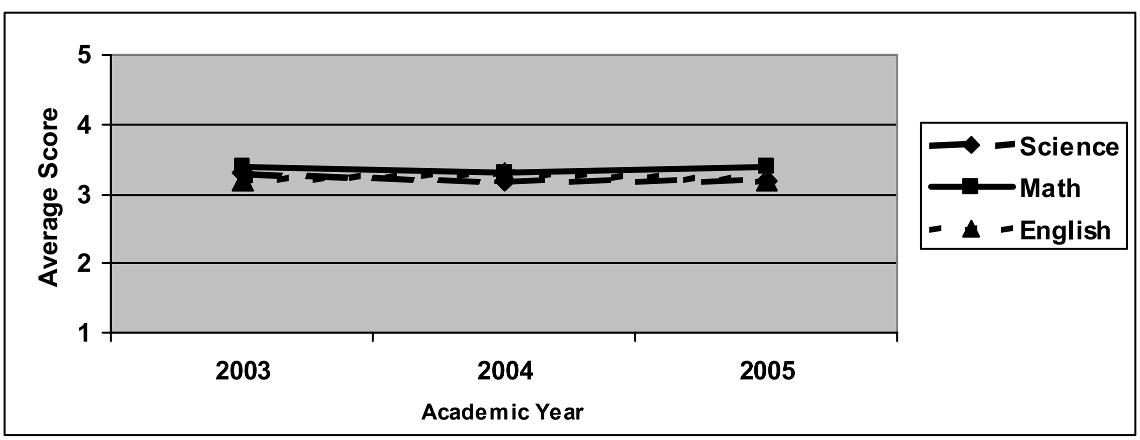

Figure 24: Average New Jersey AP scores by department.

Figure 25 shows the school's performance using the AP Metric. This was normalized to state data by dividing the number of AP points scored per student at the school by that same figure for the state. A score of 1 on this chart would indicate that the school is performing at the same level as the state; scores above 1 would represent the multiple of performance above the state; and scores below 1 reveal the fractional shortfall relative to the state.

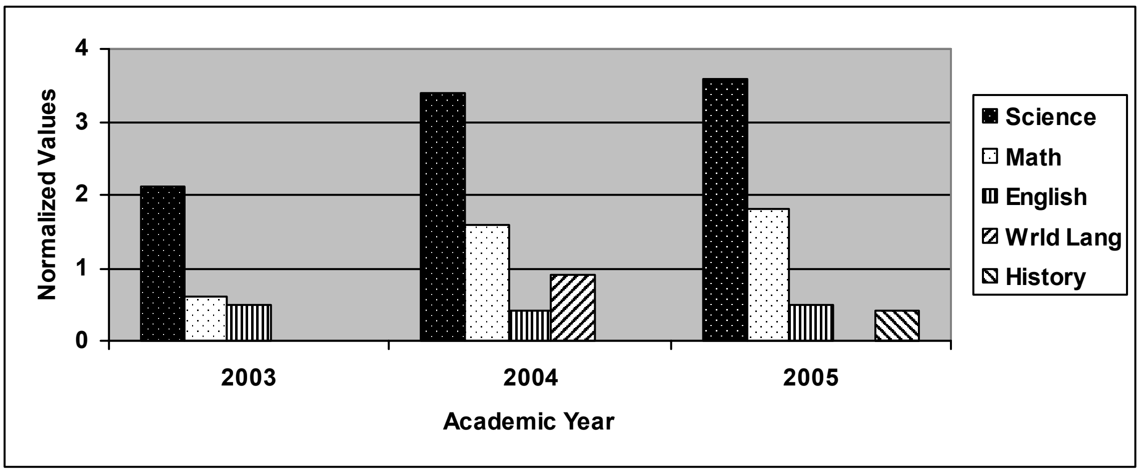

Figure 25: Normalized departmental performance as measured by the AP Metric (NJ = 1).

The school has clearly experienced a rapid growth in the number of science AP points scored per pupil: this is also true of mathematics, but to a lesser extent. While that growth has leveled in math, it is projected to continue in science. It is almost entirely due to increased participation rates, as average scores have remained at about 3.

The rapid growth that has occurred in the sciences is expected to continue as more students, not in Pre-Engineering, participate in the new science sequence and take two math courses in 9th grade. This is further evidenced by a more detailed examination of the growth in science participation down to the level of the specific courses. Since the new science sequence leads to AP Physics B first; with AP Chemistry and AP Physics C the following year; and AP Biology two years later; it would be expected that the growth trend, by course, would reveal that same layering.

This layering is in fact revealed in the following four charts: Figure 26 shows the total number of AP science exams given by year; Figure 27 presents the individual course test data; Figure 28 shows the individual test data normalized for the number of graduating seniors while Figure 29 is normalized to the state. It is clear in all of these charts that the expected pattern of layered growth by science course has occurred: the growth has been led by Physics B, followed by Physics C and Chemistry and is occurring last in Biology.

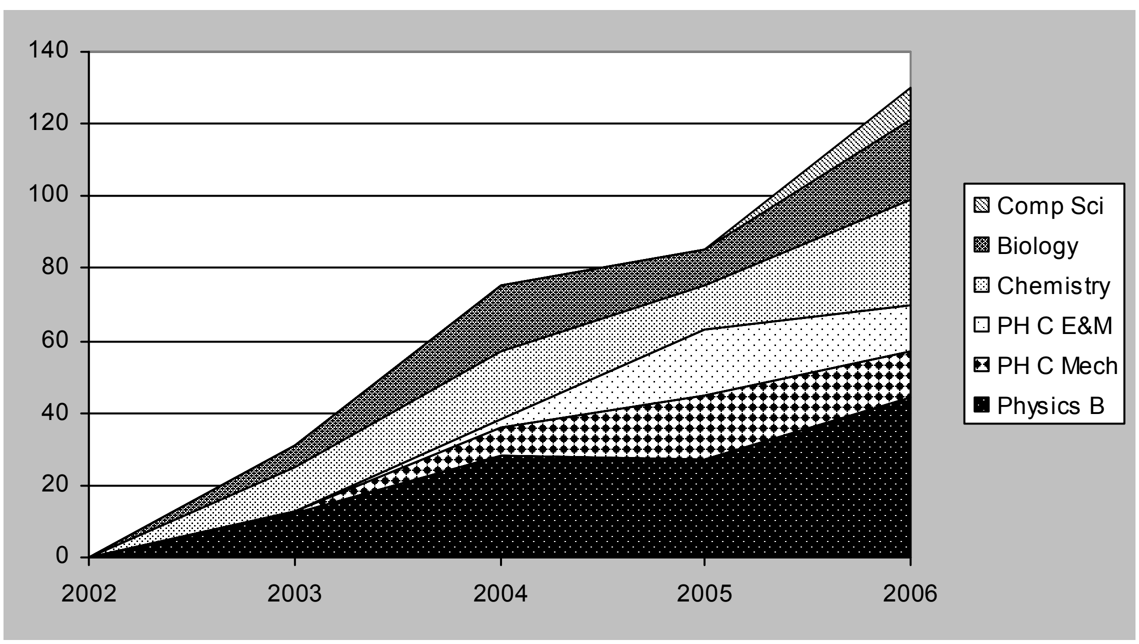

Figure 26: Science AP exams by course and in total.

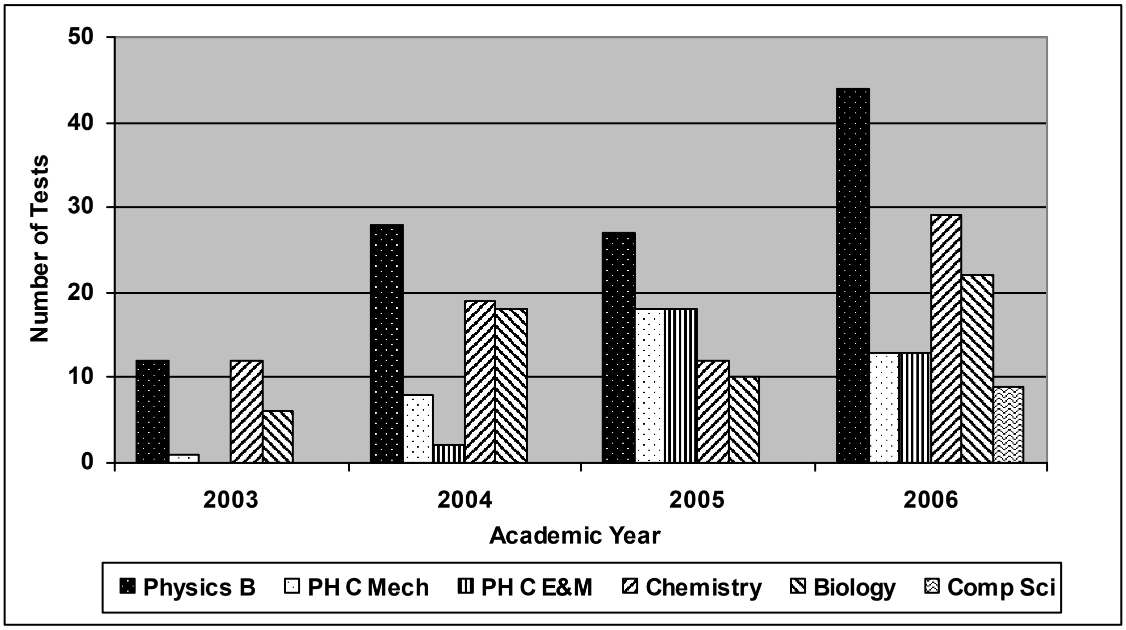

Figure 27: Science AP exams by course.

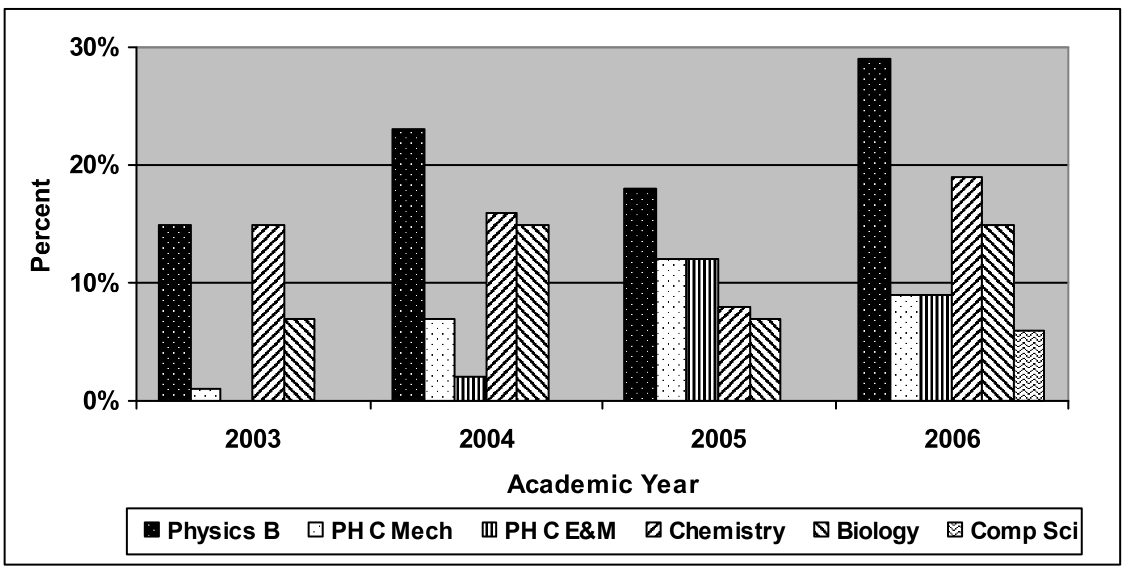

Figure 28: Science AP Participation Rate by course.

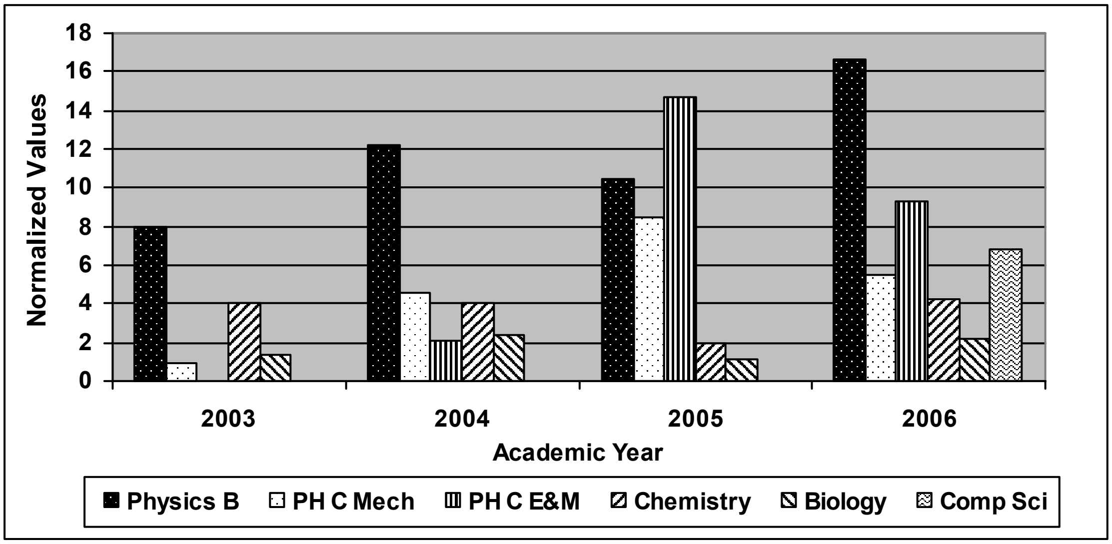

Figure 29: Normalized AP participation rates by course (NJ Rate =1).

All of these charts reveal the layered growth by course that was anticipated. Specifically both AP Physics C and Chemistry are following the growth of physics, as would be expected. Although the AP Physics C rise is greater than that of chemistry, that is a reasonable outcome due to the general strength and interest of the students in physics

Biology is also rising, but its growth is trailing behind that of chemistry, as was expected. Even though there should be some limitation in the number of students who take chemistry and biology as compared to other schools, due to the disproportionate number of students taking advanced physics courses and the limitation of the amount of time in the school day due to the requirements of the students' vocational programs, it can be seen that both biology and chemistry are being taken at rates that exceed the state average.

The only unexpected outcome in the above data is the sudden emergence of Computer Science A. That resulted from a convergence of interest on the part of Pre-Engineering students who were given the option of taking that as opposed to a second PLTW engineering course and the ITT majors, for whom it was an option in their basic program. That trend will probably continue and computer science seems to be a clear beneficiary of the analytical skills that seem transferable from mathematics and science. In fact, the teacher of that course has indicated that the Pre-Engineering students, despite never having taken a programming course before, actually outperformed the computer programming majors. She attributed that to their advanced development in analytical thinking.

While participation on Science AP exams has been growing quickly, so have the overall results. This can be seen in the following two charts (Figure 30; Figure 31) that use two different approaches to measure the AP performance: normalized passing scores and normalized AP Metric results. In both cases, the school results are compared to the state with the New Jersey rate set equal to one.

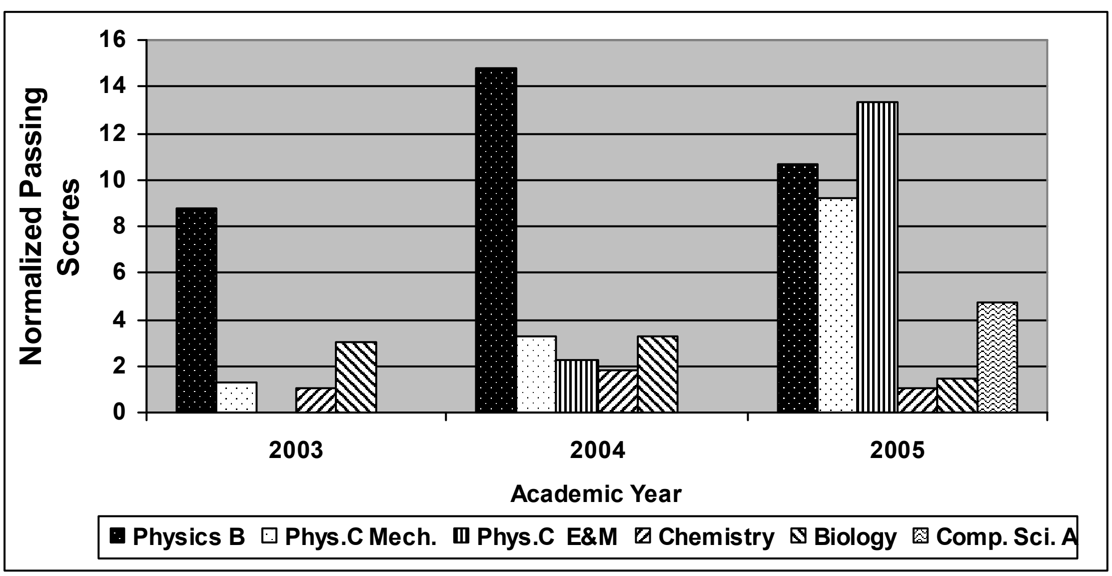

Figure 30: Normalized AP Passing Scores (3+) by course (NJ Rate =1).

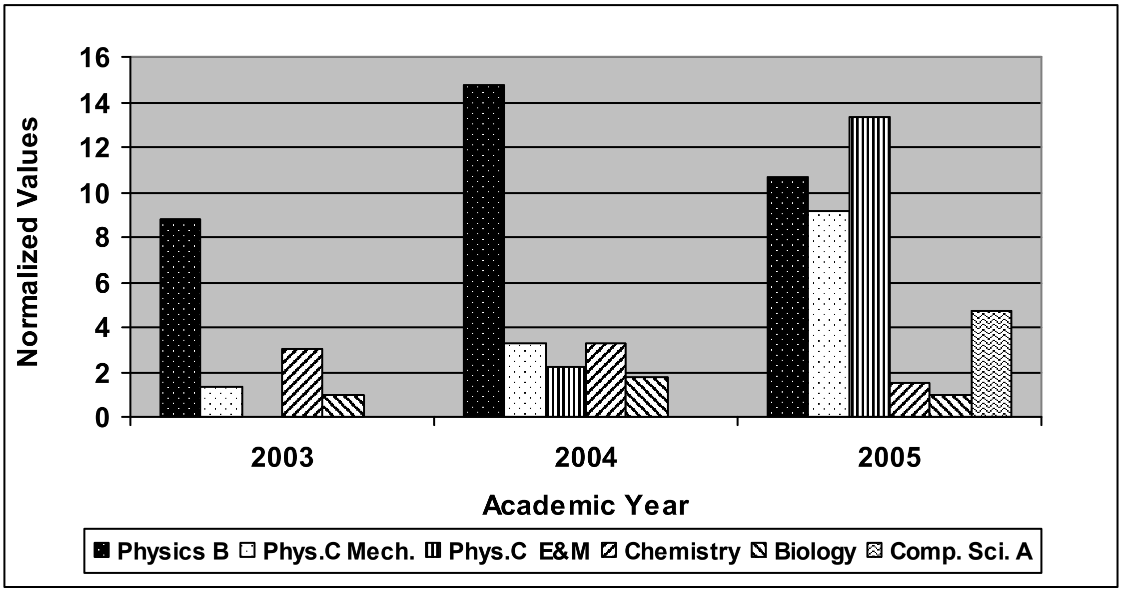

Figure 31: Normalized comparison of AP science performance by course using the AP Metric (NJ rate = 1).

Figure 30 Both Figure 30 and Figure 31 show the dramatic rise of AP Physics B and AP Physics C to levels about ten times the state average, whether measured by passing scores or by the AP Metric, in the 2005 academic year. Chemistry and biology are at about the same rate as the state in AY2005; however, the growth in their participation rates probably anticipates a rise in their AY2006 performance results as well.

While these data are consistent with the hypothesis that the science program is having a positive effect in AP participation and performance in science and mathematics relative to departments which would not have been affected by that program such as English and social studies, we also need to consider the alternative explanations.

AE1. The growth in the Asian population of the school could account for improvements in performance in mathematics and science achievement as

this demographic group has historically performed well in these disciplines.

While this explanation might seem reasonable in terms of year to year changes, it needs to explain the SAT data as well. The SAT scores of the students in the school show small parallel year to year improvements in math and verbal aptitude, while their AP results show rapidly diverging levels of achievement in those areas. Also, in the later years the AP data show wide differences in achievement between math and science versus English and Social Studies when compared to the overall state, while the SAT scores of the students in math and English are both similar to each other and just barely above that of the overall state. Certainly the high level of AP performance in math and science are not consistent with the small difference in SAT scores. Supporters of this explanation have to show why the SAT results do not also mirror the changing demographic.

AE2. The differential performance between science and mathematics versus English and social studies could be accounted for by the growth in the Asian and Hispanic population. Both these groups have a higher proportion of students that speak English as a second language and may have weaker performance in subjects that require English language skills.

This explanation is very similar to AE1, but is based on the issue of language rather than race. It faces the exact same problems with regard to the SAT data. If a student had difficulty on AP English or social studies tests due to their language, one would expect that they would also have trouble on the SAT

Verbal test: but these students scored above the state average on that test. Also, none of the students in the school require, or receive, English as a Second Language (ESL) support. This would certainly argue that there is not a serious language problem at the school. Again, supporters of this explanation would have to show why the SAT data fail to support it.

AE3. Outside factors in the community or internal factors, such as the influence of guidance counselors, etc. could be playing a role.

This is likely a factor in the complete explanation; the question is whether it is a cause or effect: it may well be both. If the science and math programs were not considered to be unusually good at the school, there is no reason to expect that the four guidance counselors at the school would steer their students to it more than would be the case in schools across the state or from year to year. The same would apply to other outside influences such as parents, siblings, friends, etc.

The comparisons to the state and from year to year require an explanation as to why these influencers have decided to encourage students in the direction of taking more science courses and more science and math AP courses. Even given that, one would still need to explain why the students, once in the courses, perform so well in them. Just because students are encouraged to do something does not mean that they will do it; and it certainly does not mean that they will do it well.

On the other hand, this could well be a supporting explanation: once the program was proving effective the students in the school would be drawn to the program at the same time as guidance counselors, friends and other influencers would push them in that direction. This would support the underlying trend and would represent a beneficial cycle.

AE4. Apparently high performance in mathematics and science as compared to English and social studies could reflect weakness in the English and social studies programs and/or the faculty in those departments rather than strengths in the science and mathematics program.

This explanation probably also contributes to the overall explanation. Certainly weaknesses in other departments in the school would result in higher levels of participation in mathematics and science. Students need to study something, so a weakness in one area will tend to create a relative strength in another. While this is probably one factor, the question is how strong a factor is it? While the result of this factor should increase participation in science and math AP courses, it should also lead to students taking high numbers of "easy" non-AP electives, for instance art, music, etc. While this would argue that weakness in other departments might well be a factor; that also is another way of saying that there must be strength in the science and math programs. In a sense, that supports the original hypothesis.

Also, signing up for an AP class is a lot easier than succeeding in it. If the program were not effective students might sign up, since it might be better than other alternatives, but there is no reason to expect that they would succeed in such large numbers if the program were not effective. This aspect would support the original hypothesis.

AE5. The performance of the mathematics and science program might be due to other strengths in those programs, not related to the hypothesis, or the strength of the faculty.

This study will not be able to address the difference between this explanation and the hypothesis of the study. It is unlikely, but possible, that faculty alone could be the difference. There are nearly twenty faculty members teaching math and science at the school and it’s unlikely that they are on average very much different than that of other schools. While that is possible, it would raise the question as to how that occurred. It is currently more difficult to hire high quality math and science teacher than English and social studies teachers. Vocational / technical schools are not generally the first choice of academic teachers so this would seem to make hiring those teachers problematic for a school like ours. One explanation would be the attractiveness of the science and math program at the school: making this a secondary explanation. However, there is no measure of faculty quality that was used in this study which could extract faculty ability from the data obtained.

Also, it is very possible that the program is successful for reasons that are not obvious. That would be difficult to determine in any circumstance and must be considered as other schools move to adopt this program. As will be discussed in chapter five, the adoption of this program at other schools may be a good way that the difference between this explanation and the hypothesis can be explored.

AE6. As a vocational / technical school, this site could be particularly fertile for mathematics and science and the opposite might be the case for English and social studies.

This explanation is reasonable in terms of the more likely association between student interests in technical fields such as Computer Science, Automotive Service or Pre-Engineering and mathematics and science versus English and social studies. It is less clear how that would relate to student interests of those who are majoring in Cosmetology, Fashion Design or Law and Justice. However, it is the case that AP participation is considerably higher among the former group of students so could certainly be an explanation.

It is unlikely to be a primary explanation in that high AP results are not associated with vocational / technical schools in general. In fact, a cursory review of other such schools in New Jersey has yet to identify any that offer any AP courses. While a more thorough review could be a part of future research, even this preliminary study makes it unlikely that vocational / technical school are competitive, or perhaps even present, in this category. So while this explanation could be reasonable in terms of the differential between AP exams taken in different departments, it has the burden of explaining why any are taken at all.

Also, since a sister school of the school under study is a magnet school, with programs in mathematics, science, technology and engineering, there is a natural drain of students with a strong interest in those fields from our school.

Students who are identified, or believe themselves to be capable in those areas, do not attend the school under study, they stay in their home school or attend the magnet school. However, this explanation could be contributing more of an effect as the reputation of our school in these areas grows. Therefore, it must be considered as a possible primary or secondary explanation.

Analysis of HSPA Results

The answer to the fifth research question, "How does the HSPA performance of the students in this program compare to that of students in other New Jersey schools and to their English HSPA performance?" is provided in this section. The High School Proficiency Examination (HSPA) is given to all New Jersey 11^{th} grade students. In theory, scoring at the "Proficient" level on both the Language Arts and the Mathematics HSPA is required in order to obtain a high school diploma (in practice, an alternative assessment, the SRA, is often used to bypass this requirement). Student scores fall into three categories of proficiency: Partial, Proficient or Advanced. To be considered Proficient a student must obtain a score of 200: a score of 250 is considered Advanced. The figures for all schools in the state, as well as for the overall state are published annually in the New Jersey school report card: the source of the figures used below.

A common misunderstanding that occurs in evaluation year to year performance in data of this sort is to forget that each year represents a different cohort of students. Thus, changes from year to year reflect a combination of factors including both the program as well as the students who are taking the assessment in that year. This should be kept in mind when considering these results.

Table 6 gives the school and the state HSPA data for AY2004 and AY2005 for both mathematics and language arts. This same data is shown graphically in Figure 32 and in Figure 33. In terms of the math results, there are two very important findings. First, in AY2005, the percentage of students in the school who were Advanced Proficient on the Math HSPA was 41%: the state percentage was 28%. In the prior year, the school percentage was about the same as that of the state: 24%. This shows that there has been a dramatic increase in the number of students in the school who are considered very strong in mathematics relative to the state. Second, the percentage of students at the school who were not Proficient fell from 15% in 2004 to under 1% in 2005 (representing just one student). The state average for students who were not Proficient was 30% in 2004 and 24% in 2005. The combination of these results indicates that student achievement in mathematics at the school has been improved significantly relative to the state.

Math	Year	# Tested	Proficiency Percentages		
			Partial	Proficient	Advanced
School	AY2005	154	0.6%	58.4%	40.9%
	AY2004	104	15.4%	60.6%	24.0%
State	AY2005	93939	24.5%	47.1%	28.1%
	AY2004	90712	30.0%	45.6%	24.5%
Language Arts	**Year**	**# Tested**	**Proficiency Percentages**		
			Partial	**Proficient**	**Advanced**
School	AY2005	154	1.3%	83.1%	15.6%
	AY2004	104	3.8%	77.9%	18.3%
State	AY2005	94858	16.8%	63.6%	19.6%
	AY2004	90946	17.8%	65.0%	17.2%

Table 6: School and State HSPA Results for AY2004 & AY2005

This dramatic improvement can be seen in Figure 32, which shows the year to year data for the school and the state. In the school data, the number of students who were not proficient virtually disappears in AY2005, while the number of students who achieved Advanced Proficiency is above 40%.

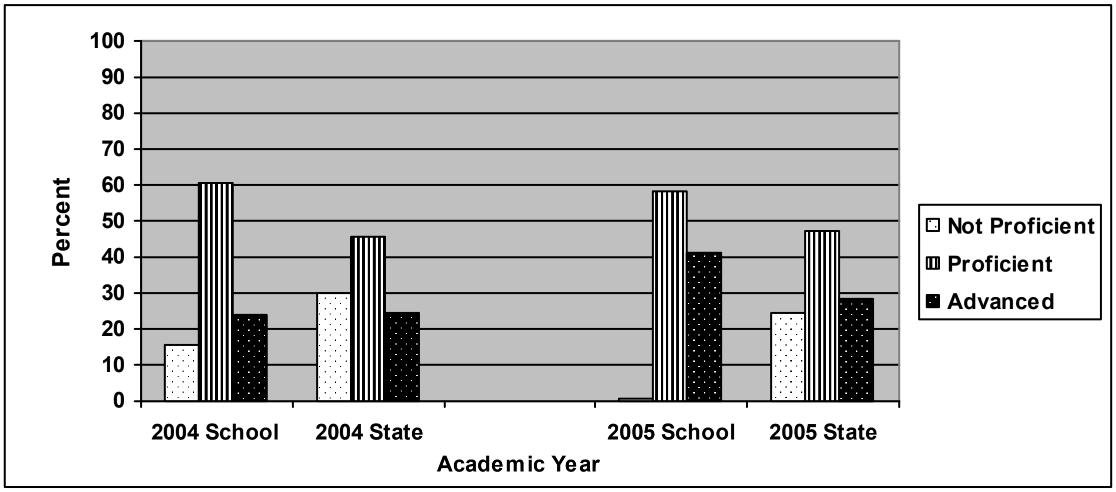

Figure 32: Math HSPA results for the school and the state.

The gains at the top end of the scale, the percentage of students who are Advanced Proficient, cannot be attributed to a general increase in student aptitude at the school. First, these gains are much larger than would be reflected by the small improvement in SAT scores that were reported above. While there has been an improvement in SAT scores, it has been on the order of about 25 points, certainly not enough to have created such a dramatic shift in performance, a 70% increase in the number of students who were judged Advanced Proficient in mathematics, to a figure that is 45% above the state average.

Second, if this were due to a general improvement in student aptitude it should also have led to a similar improvement on the Language Arts HSPA: especially since the school's students scored better than the state average by about the same amount on both the Math and the Verbal SAT: by this measure their aptitude in math and verbal ability should be comparable. Also, the year to year improvement in SAT performance was about the same for math and verbal. As can be seen in Table 6 and Figure 33; there was no comparable improvement in the percentage of Advanced Proficient students in the school, relative to the state, on the Language Arts HSPA.

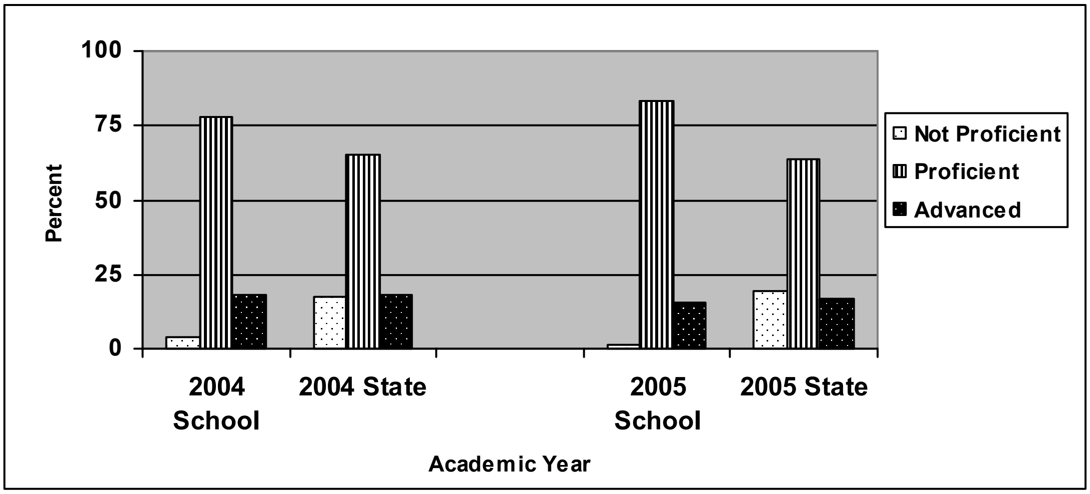

Figure 33: Language Arts HSPA results for the school.

In AY2005, the percentage of students in the school who were Advanced Proficient on the Language Arts HSPA was 16%: in that same year the state percentage was 20%. In the prior year, the school percentage was 18% while the state percentage was 17%. The percentage of the school's students who were judged Advanced Proficient on the Language Arts HSPA declined last year and has remained at or below the state average. Given that the school's students have Verbal and Math SAT's scores that are comparable to those of the state's figures, and to each other, this represents an indication that programmatic differences might well account for the exceptional performance of the school's students on the Math HSPA.

In Figure 34, the relative performance of the students in the school by the measure of Advanced Proficiency on the HSPA is shown by normalizing both the math and the language arts statistics to that of the state. I did this by dividing the percentage of students achieving Advanced Proficiency in the school by that same percentage for the state. It is clear from this that the only improvement was in mathematics, and that that improvement was dramatic.

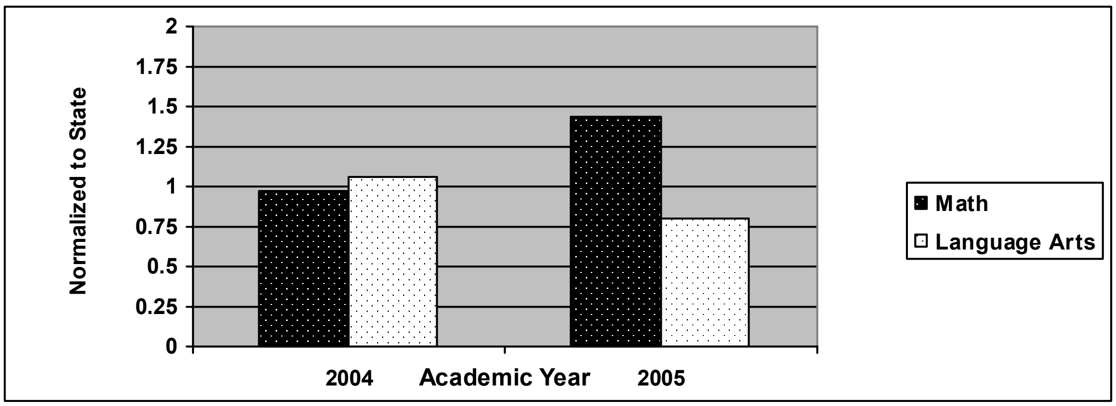

Figure 34: Number of Advanced Proficient students relative to the state (NJ =1).

It is important to point out that the school does not offer any courses to prepare students for the Math or Language Arts HSPA's. The results that have been achieved are reflective of the school's normal academic programs.

While the cause of this improvement in mathematics achievement cannot be known with certainty; it is clear that student achievement in mathematics is improving relative to both the state and relative to Language Arts. These facts certainly support the plausibility of the argument that the new science/mathematics program is having a beneficial effect: certainly a contrary result would have hurt the plausibility of that argument. However, we need to once again consider the alternative explanations.

AE1. The growth in the Asian population of the school could account for improvements in performance in mathematics and science achievement as this demographic group has historically performed well in these disciplines.

Supporters of this explanation need to address the lack of correlation between SAT results and HSPA results. The SAT scores of the students in the school show small parallel year to year improvements in math and verbal aptitude, while their HSPA results show rapidly diverging levels of achievement in those areas. The HSPA data for 2005 show wide differences in the percentage of students who are judged Advanced Proficient in mathematics versus language arts: the school is more than 40% higher than the overall state in mathematics but more than 20% below the state in language arts. This effect is quite large while the difference in relative performance to the state on the math and verbal SAT tests is quite small: 12 points above in math and 9 points above in verbal for that same cohort. Certainly the high level of HSPA performance in math and science are not consistent with the small difference in SAT scores. As was the case with the AP results, supporters of this explanation have to show why the SAT results do not also mirror the changing demographic.

AE2. The differential performance between science and mathematics versus English and social studies could be accounted for by the growth in the Asian and Hispanic population. Both these groups have a higher proportion of students that speak English as a second language and may have weaker performance in subjects that require English language skills.

Once again, this is similar to AE1 and has the same burden of explaining why these differences do not show up in the SAT results. This requires believing that the aptitude measured by the SAT verbal test is irrelevant for measuring likely performance on the Language Arts HSPA. While this is possible, research would have to be done showing that the SAT is easier for students for whom English is a second language than is the HSPA. If that is the case, it would be important for the state to be made aware of that since it would affect the graduation rates of that group and not be correlated to their likely success in college.

AE3. Outside factors in the community or internal factors, such as the influence of guidance counselors, etc. could be playing a role.

This explanation would only apply to these HSPA results in a secondary sense. It would have to be shown that these results are due to course choices recommended by these influencers: that due to them students took courses that better prepared them for the math HSPA than for the language arts HSPA. However, that would still require that those recommended courses were effective in accomplishing that preparation: which would require invoking one of the other explanations as well.

AE4. Apparently high performance in mathematics and science as compared to English and social studies could reflect weakness in the English and social studies programs and/or the faculty in those departments rather than strengths in the science and mathematics program.

This would explain the relatively poor results on the language arts HSPA but would not address the very high percentage of students who are Advanced Proficient on the 2005 math HSPA. However, it could serve as a partial explanation if used in conjunction with another explanation that accounted for the high math results.

AE5. The performance of the mathematics and science program might be due to other strengths in those programs, not related to the hypothesis, or the strength of the faculty.

The relevance of this explanation to this HSPA data is really the same as was discussed for it vis-à-vis the AP data in the section above.

AE6. As a vocational / technical school, this site could be particularly fertile for mathematics and science and the opposite might be the case for English and social studies.

While this explanation has some merit in terms of the low scores on the language arts HSPA results, it does not address the unusually high scores on the mathematics HSPA in 2005. It also does not address the lack of correlations with SAT results. Traditionally, vocational / technical schools have not performed particularly well on state exams of any sort. A preliminary review of other such schools in New Jersey confirms that: they typically have low percentages of students who are Advanced Proficient in either math or language arts. However, to fully explore this explanation further research into the results of a broader spectrum, perhaps all the vocational / technical schools in New Jersey, would need to be conducted.

Analysis of Participation in Science Electives

The answer to the sixth, and final, research question, "What are the trends in the participation rate in science electives?" is answered in this section. Another measure of the effectiveness of the science program is the number of science courses that students elect to take each year: a proxy for their interest in science and/or their belief in the value of studying science. This measure is to a significant extend confounded with the growth in AP participation reported above, since most science electives are AP courses. However, while all AP courses are elective, there are additional non-AP science electives.

Figure 35 and Figure 36 show the trend in participation in all science electives.

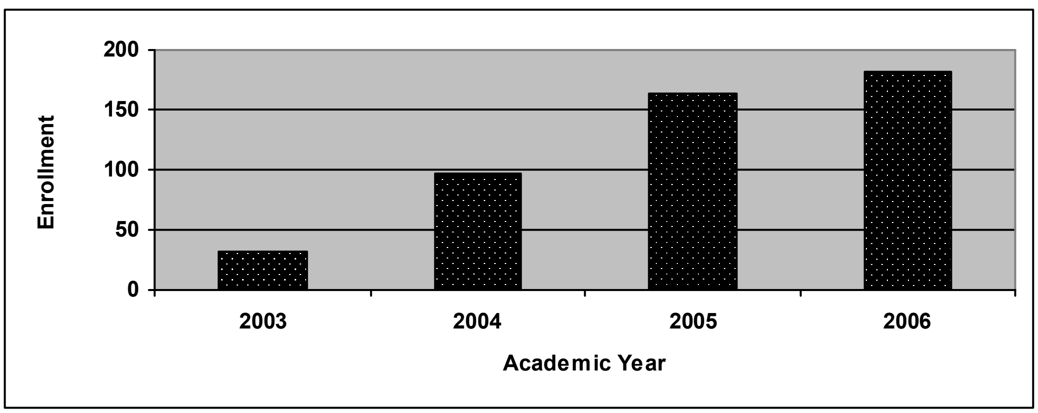

Figure 35: Total enrollment in science electives.

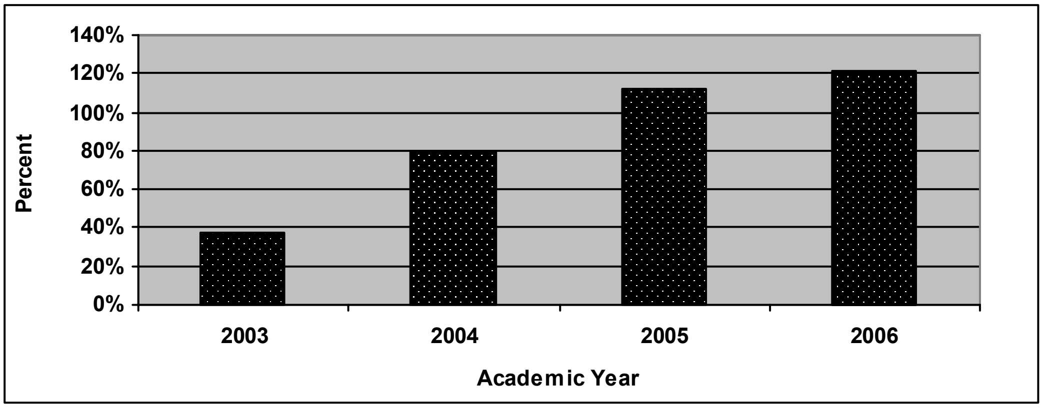

Figure 36: Total participation rate in science electives (total science elective enrollment divided by the number of graduating seniors).

Clearly the interest in studying science at the school has grown a great deal over the years. The school requires students to take three years of science. In addition, the Law & Justice program requires its students (about 20 this year) to take a fourth year: Forensics Science. Combining those required courses with the 120% science elective participation rate in AY 2006, leads to the result that the average student in the school is taking 4.3 years of science; well above the 2 or 3 years of science being taken at many schools.

The breakdown of the courses being taken is shown in Figure 37 and Figure 38. Interestingly, two non-AP courses are among the most popular in the school: Anatomy & Physiology is the second most popular and Earth science ranks as the fifth most popular science elective. The interest in these courses indicates a general interest in science: not just an interest in getting AP credit for science course.

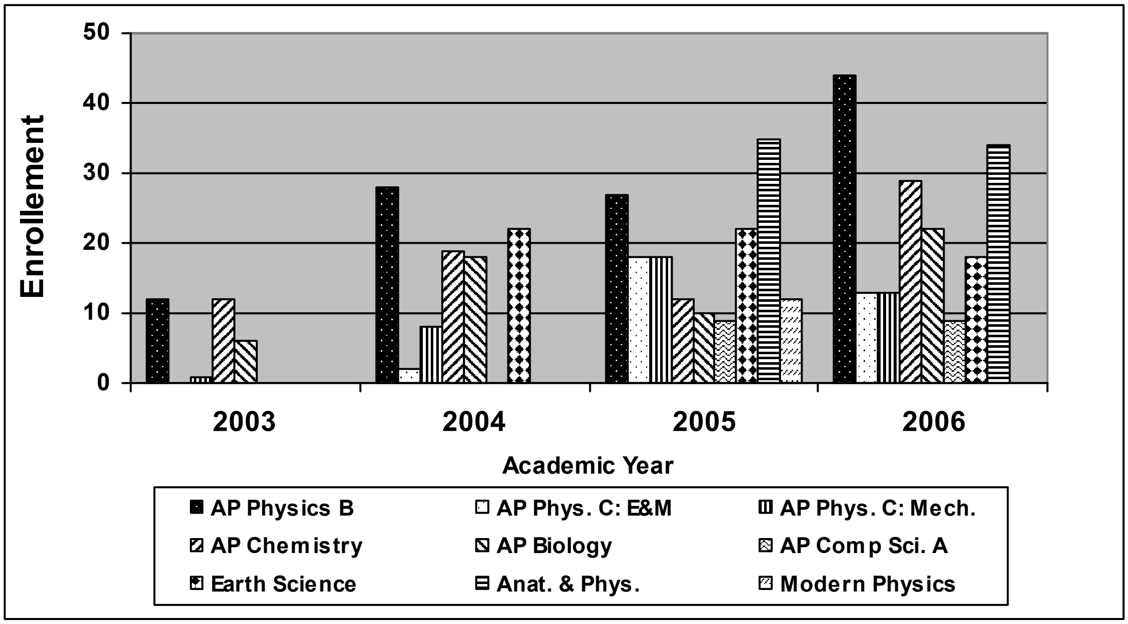

Figure 37: Enrollment in science electives by course.

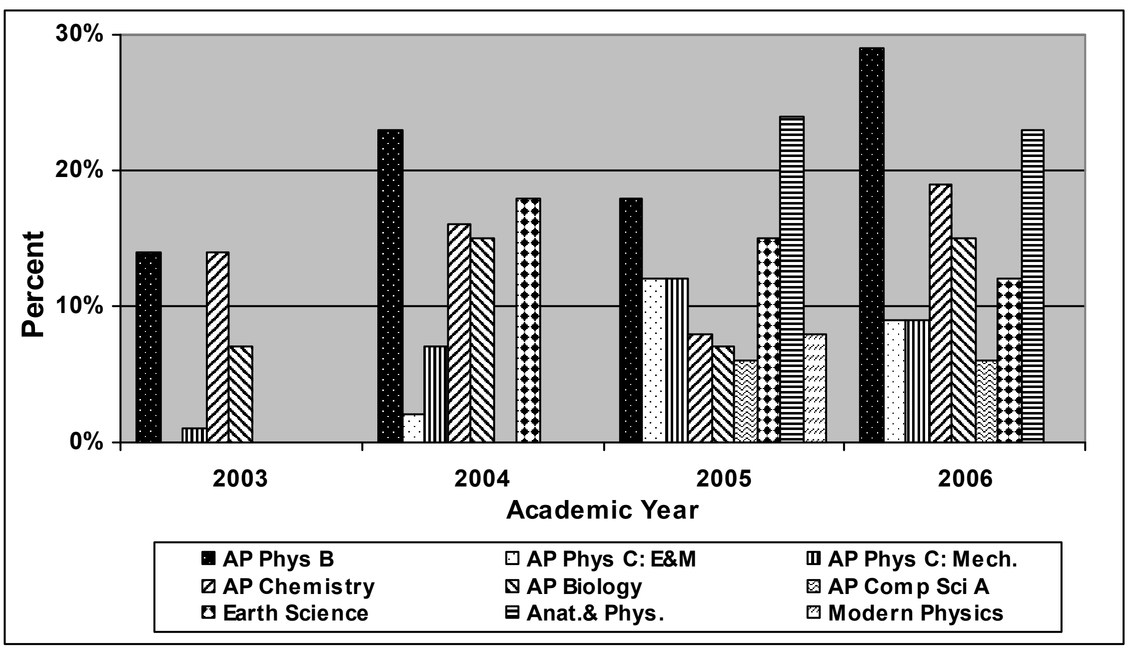

Figure 38: Participation rate in science electives by course.

Once again, while the program under study is one explanation for this very high level of participation in science electives, many alternative explanations are possible. These include:

AE1. The growth in the Asian population of the school could account for improvements in performance in mathematics and science achievement as this demographic group has historically performed well in these disciplines.

This explanation is reasonable as a contributing factor in the year to year data as there may well be a demographic explanation for an increased interest in science and mathematics versus English and social studies. In this case, the comparable SAT scores would not be a problem as they measure aptitude not interest or cultural influence, and participation rates might well be more affected by interest and perceived value rather than aptitude.

However, even in the last year of the study, AY2005, the percentage of the school which is Asian only reached 20% while the percentage, based on courses taken divided by the number of graduating seniors, taking science electives reached 120%. This makes it unlikely for this to be the sole explanation. Also problematic for this explanation is the fact that the growth in Asian population would still have been mostly in the 9th and 10th grade in AY2005: 9th graders cannot take a science elective and only a small percentage of 10th graders in specific majors have room in their schedules to take the one science elective that would be open to them: AP Physics B. So while this explanation may play a role in an overall explanation, it cannot stand alone.

Interestingly, this explanation might also be more an effect than a cause. As the results of the school in mathematics and science have become more known in the county, the school might be more attractive to students whose culture values science and mathematics education. That might explain a growth in that demographic at the school. If that is the case, it would be expected that the trends seen here will continue and may accelerate.

AE2. The differential performance between science and mathematics versus English and social studies could be accounted for by the growth in the Asian and Hispanic population. Both these groups have a higher proportion of students that speak English as a second language and may have weaker performance in subjects that require English language skills.

As was the case for AE1, this explanation is reasonable as a contributing factor in the year to year data as there may well be a linguistic explanation for an increased interest in science versus English and social studies. Students who feel less comfortable or capable, speaking or reading English might be less likely to choose electives in English or social studies than in mathematics or science. In this case, the comparable SAT scores would not be as problematic as they measure aptitude not interest or comfort level, and participation rates might well be more affected by those factors than by aptitude.

In this case, the percentage of Hispanic and Asian students in AY2005 was nearly 45% of the school: a percentage large enough to have more significantly affected these results.

This would indirectly explain the high participation rates in science because students need to take some electives: if they don't choose those that require strong language skills, it makes it more likely that they will take those that do not. While this could lead them towards electives in art, music, etc. as well, they would be advised by their guidance counselors to take more "academic" electives in order to be admitted to better colleges. Thus this explanation, in conjunction with the following AE3, could partially explain these results.

AE3. Outside factors in the community or internal factors, such as the influence of guidance counselors, etc. could be playing a role.

This is probably where this factor would have the greatest impact. It is easy to imagine guidance counselors pushing students towards science courses in order to bolster their transcript. However, it is unclear why that would be more true at this school than others unless it follows from the established success of the science program. In that case, it might be reinforcing an established pattern.

However, as noted in the above discussion of AE2, the need to take academic courses coupled with a population that is less comfortable in English could contribute to the overall explanation of the participation trends at the school.

AE4. Apparently high performance in mathematics and science as compared to English and social studies could reflect weakness in the English and social studies programs and/or the faculty in those departments rather than strengths in the science and mathematics program.

This explanation could also work in conjunction with AE2 and AE3 to provide an alternative overall explanation. Guidance counselors would encourage students to take courses in which they are more likely to benefit and which would look good on their transcripts. If they view the other academic departments as weak, they will encourage students towards the relatively stronger departments. That strength is not necessarily due to the hypothesis under study; it could just be that the science courses aren't as "bad" as the other academic courses and students need to take something.

AE5. The performance of the mathematics and science program might be due to other strengths in those programs, not related to the hypothesis, or the strength of the faculty.

This study is not able to tease out why students might consider the science courses more attractive than other alternative electives. Determining that will require further research: probably qualitative research.

AE6. As a vocational / technical school, this site could be particularly fertile for mathematics and science and the opposite might be the case for English and social studies.

To the extent that students need to take academic electives, this explanation is very relevant. Certainly students who are more technically inclined might be less interested in taking English, social studies, etc. While other electives, such as art and music, or other vocational and technical electives, like culinary, computer aided design, etc, might also be appealing, they would not fulfill their transcript requirement for academic courses.

CHAPTER 5: DISCUSSION

The Research Questions

The first three research questions related to the documentation and description of the science program at the school under study. These questions were:

- What is the new science sequence and how is it unique?
- What are the new physics curricula and how are they unique?
- What is algebra-based 9^{th} grade physics and how is it taught?

The overall objective of these three questions was to supply enough information that another school could implement this program. The documentation requested in these questions was furnished in the Results section and the Appendixes of this dissertation. Together, the answers to these three research questions supply enough information that a capable school could begin the implementation of this program. However, it would still be challenging for most schools to proceed with this information alone.

Additional support that would help schools who chose institute this program would be the completion of the textbook that is being written as well as a laboratory manual that would describe experiments that would support the launch of the new courses. While work on those, and other materials, will continue, their completion was beyond the scope of this dissertation.

The last three research questions represented different approaches to try to get the answer to the overriding question: is this program having a positive effect on math and science achievement in the school?

- How does the AP performance of the students in this program compare to that of students in other New Jersey schools?
- How does the HSPA math performance of the students in this program compare to that of students in other New Jersey schools and to their Language Arts HSPA performance?
- What are the trends in the participation rate in science electives?

The answers to all three of these research questions were positive and consistent with what would have been anticipated if the program were functioning as expected. The answer to each of these questions contributed towards answering the bigger question regarding the program's effectiveness. Not only were the answers positive, they were also in keeping with what was predicted based on the nature of program and the manner in which it was established.

For instance, the AP participation rates for each of the science courses are growing as would be expected as students move through the program; with physics the largest, followed by chemistry then followed by biology. The consistency between the theoretical outcomes of the program and the data obtained from this study reinforces the data's validity.

While no single set of data can prove that this program is effective: the combination of all the data that were obtained in answering these research questions strongly supports the idea that it is having a positive effect. However, as was noted in each section in which those results were furnished, there are alternative explanations for each of them. In general, the changes that occurred at the school during the implementation of the program and the fact that the data necessarily related to these changing cohorts with time makes it difficult to determine if the program was the cause of the results that were reported. There are specific alternative explanations that might be the true cause and some research ideas that might support, or fail to support them.

Alternative Explanations and Implications for Future Research

AE1. The growth in the Asian population of the school could account for improvements in performance in mathematics and science achievement as this demographic group has historically performed well in these disciplines.

As was indicated above, supporters of this explanation will have to deal with the data that show that the SAT scores of the students in the school showed parallel year to year improvements in math and verbal aptitude, while their results show rapidly diverging levels of achievement in those areas. Also, in the later years the AP and HSPA data show wide differences in achievement between math and science versus English and Social Studies when compared to the overall state, while the SAT scores of the students in math and English are both similar to each other and just barely above that of the overall state. Certainly the high level of AP performance in math and science and HSPA performance in math are not consistent with the small difference in SAT scores.

While this explanation is consistent with the higher participation rates in science electives, it does not seem of sufficient scale to explain those results on its own: however, it may be a contributing factor.

Also, the demographic shift in the school might be a result not a cause of the results of the study. As the school has performed better, it may be attracting students whose culture puts greater emphasis on mathematics and science education.

Future Research

FR1. In order to support this explanation, it would have to be shown that the SAT was not a good predictor of achievement on AP and HSPA results as compared to the racial composition of a school population. A quantitative study of correlations between SAT results; AP performance; HSPA performance; and demographic factors would be valuable.

FR2. This explanation could also be tested by instituting this science program at a school whose population is stable and of a significantly different demographic character. A study of the outcomes at that new site would either support this explanation or not.

FR3. The school data could be disaggregated to see if there are demographic trends that explain them.

AE2. The differential performance between science and mathematics versus English and social studies could be accounted for by the growth in the Asian and Hispanic population. Both these groups have a higher proportion of students that speak English as a second language and may have weaker performance in subjects that require English language skills.

This explanation is very similar to AE1, but is based on the issue of language rather than race. It faces some of the same problems with regard to the SAT data, but less so in some instances. On the one hand, if a student has difficulty on AP English or social studies tests or the Language Arts HSPA due to their language, one would expect that they would also have trouble on the SAT Verbal test: but these students scored above the state average on that test. Also, none of the students in the school require, or receive English as a Second Language (ESL) support. This would certainly argue that there is not a serious language problem at the school.

On the other hand, it is possible that students might be able to perform in a second language but not be as attracted to subjects that require them to do so. Thus, the participation rates on electives could be better explained by this than by AE1.

Future Research

FR4. In order to support this explanation, it would have to be shown that the SAT was not a good predictor of achievement on AP and HSPA results as compared to the first language of a school population. A quantitative study of correlations between SAT results; AP performance; HSPA performance; and first language would be valuable. This might be done in conjunction with FR1.

FR5. This explanation could also be tested by instituting this science program at a school whose population is stable and of a significantly different linguistic character. A study of the outcomes at that new site would either support this explanation or not. This might be done separately or in conjunction with FR2.

FR6. The school data could be disaggregated to see if there are linguistic trends that explain them. This might well be combined with FR3.

AE3. Outside factors in the community or internal factors, such as the influence of guidance counselors, etc. could be playing a role.

This is likely a factor in the complete explanation; the question is whether it is a cause or effect: it may well be both. If the science and math programs were not considered to be unusually good at the school, there is no reason to expect that the four guidance counselors at the school would steer their students to it more than would be the case in schools across the state or from year to year. The same would apply to other outside influences such as parents, siblings, friends, etc.

The comparisons to the state and from year to year require an explanation as to why these influencers have decided to encourage students in the direction of taking more science courses and more science and math AP courses. Even given that, one would still need to explain why the students, once in the courses, perform so well in them. Just because students are encouraged to do something does not mean that they will do it; and it certainly does not mean that they will do it well. Also, this would still leave the HSPA scores left to explain. If the students were taking these courses that would not necessarily affect their HSPA results unless the courses were effective.

On the other hand, this could well be a supporting explanation: once the program was proving effective the students in the school would be drawn to the program at the same time as guidance counselors, friends and other influencers would push them in that direction. This would support the underlying trend and would represent a beneficial cycle.

Future Research

FR7. Research that would support, or fail to support this explanation would be qualitative in nature. Interviewing parents, guidance counselors and students at this and other sites might reveal differences in what is being promoted by the community, inside and outside the school.

AE4. Apparently high performance in mathematics and science as compared to English and social studies could reflect weakness in the English and social studies programs and/or the faculty in those departments rather than strengths in the science and mathematics program.

This explanation is supported by the differential results between English and social studies versus science and mathematics. To the extent that only the differences in performance between those areas were considered, this explanation would be plausible. It is also most likely a factor in any complete explanation. However, it fails to explain the very high levels of student achievement in mathematics and science compared to the state. It seems unlikely that students are achieving AP and HSPA results that are so far above the state level in mathematics and science because their English and social studies programs are weak.

Future Research

FR8. A new English and social studies program could be instituted at the current site: a program that would follow the approach used in the current mathematics and science program. Changes in student achievement in the areas of English and social studies as well as in science and mathematics would support, or fail to support, this explanation and/or the hypothesis of this study. Since there would be significant interactions, especially in participation rates, this study would be both rich and complex to interpret. But its implications would be important for education in all of these disciplines.

AE5. The performance of the mathematics and science program might be due to other strengths in those programs, not related to the hypothesis, or it could be due to the strength of the science and math faculty.

It will always be difficult to tease out the reasons for a program's success or failure. Certainly any program that is implemented poorly and by an incompetent faculty will fail. Similarly, even a poorly designed program based on a badly thought out theory could be made successful by a sufficiently talented faculty and by exceptionally competent implementation. The faculty will simply adjust what they do in the classroom to make it work: what is done in the classroom might not match the theory at all. As a result, there will always be an interaction between the effects due to the competence of the staff and the theory being expressed in the program.

Future Research

FR9. A qualitative study of the students at the current site as to their perceptions of what they experienced in their courses and to what they ascribe their successes and failures. A well-designed study should address the questions as to whether what occurred in the classroom was perceived as consistent with the theoretical program design and how students perceived the effectiveness of whatever did occur.

FR10. If the program is instituted at new sites, a study such as FR9 should be conducted, before, during and after its implementation to track changes in student perception.

AE6. As a vocational / technical school, this site could be particularly fertile for mathematics and science and the opposite might be the case for English and social studies.

Vocational / technical schools are not traditionally associated with high academic performance. While that has continued to be true at this school, with respect to English and social studies: it is not the case with respect to science and mathematics. While this explanation makes the case that it might be more likely to occur in science and math at a vocational school, it does not explain why it happened at all. It is not clear that any AP courses are offered at any other schools of this type in New Jersey. In that sense, this school is also performing well above other schools of its type in the areas of English and social studies: just not as well as in mathematics and science.

Similarly, the HSPA results of the school would be expected, based on this explanation, to be better in mathematics than in language arts: and that is the case. But this does not explain why they are so much better than a typical

New Jersey school and those vocational / technical schools that were quickly identified.

The same questions exist with regard to participation rates in science electives: this explanation makes sense as to why they would be high relative to other electives, but not why they are so high at all. In most vocational / technical schools, it is challenging to get students to take three years of science; let alone 1.2 years beyond those three years.

So this seems to represent a partial explanation: it may explain why math and science are more likely to prosper at a school of this sort as compared to English and social studies; but it does not explain why any of them prosper.

<u>Future Research</u>

FR11. Data for all the vocational / technical schools in New Jersey could be collected and all the comparisons that were done in this study could be extended to that group of schools. This analysis would very directly either support or fail to support this explanation.

Additional future research

The present evidence is sufficient and the argument sufficiently plausible, that other schools may begin pursuing this same path. Much has been learned by the work at this school; so that path should be easier to find and follow. Each school will have to find its own way to some extent; but the approach and its value have been illuminated.

Even while the current school proceeds with refining its approaches and extending them to new subjects; even as new schools begin their own journey; it is critical that research continue into this educational approach. In the study of programs: programs that extend over years; involve hundreds of students; and rely upon scores of teachers, it is exceedingly difficult to conduct experiments or even quasi-experiments. However, it is possible to construct a theoretical framework and look for evidence that either supports or fails to support the plausibility of that framework. That is what has been done in this study.

By its nature, that sort of research is both important and limited, almost in inverse proportion. Those limitations can only be addressed by continued study; both extensions of the current study as well as new types of studies. Some suggested future research studies were discussed above. None of these studies will be able to "prove" or "disprove" the validity of this educational approach: however, these additional studies will increase or decrease its plausibility. In addition to the studies that were discussed above with regard to the alternative explanations, there are additional studies that could be done with regard to the current hypothesis.

FR12. Qualitative research should be done at the current site on student perceptions regarding the program in each of the years that they participate in it and their first years after graduating. For example, individual and group interviews with students in each of the high school grades as well as their first few years of college would be of great value. It would indicate if the benefits are perceived as real by the students while they are participating in the program and after they get into college classes with students who were in more traditional high school programs.

FR13. Quantitative research will be made possible when New Jersey begins tracking the results on the various state examinations: the state is currently in the process of creating unique student identifiers and computerizing its data. Once that is done, Value Added Measurement program exist that would allow a quantitative analysis of the effect of the program. This could be used to track the program's effect on not only state exams, but also on AP achievement. For instance, a regression analysis could use the 8th Grade GEPA results to predict student achievement on AP Exams as well as the 11th grade HSPA exam the effect of participating in this new science and math program, and the significance of that effect, could then be evaluated using those data.

Implications for Instruction

The importance of this study is not limited to understanding the effect of a new scope and sequence, curricula or pedagogy. It also reflects upon the purpose of education and the difference between education and job training; a difference that is always importance but perhaps most clearly an issue to those of us who work in a vocational / technical school. Job training is an important facet of a school such as ours, but it does not define the purpose of education.

The purpose of education is to pass along to the next generation their rightful inheritance: the mediational tools and knowledge that have been developed by their forbearers; forbearers that go back to pre-history; before the dawn of time. Those tools and that knowledge is as much a part of our phenotype as are our legs, arms and brain. However, this part of our phenotype is not passed along by our genes, but rather, by the overarching mediational tool of education. A key genetic breakthrough that propelled our species to its prominence in the natural world was the one that allowed us to transcend genetic evolution and begin progressing with the speed of sociocultural evolution: a pace that makes genetic evolution appear almost like its standing still.

The mechanism for this is education. We do not educate our young so that they can get jobs; work in fast food restaurants; become physicists; or repair cars. Those outcomes may follow from education, but education was at the root of humanity long before those specialized jobs came into existence. In fact, those jobs are just a symptom of the sociocultural progress that drives us forward.

Education has long struggled with the chimera of "relevance". The idea that each thing we teach our youth must have some direct and immediately obvious value to them. This has been, and always will be, a dead-end. It leads to arguments like, "You need to learn mathematics so you can make change when you are working a cash register": an argument which disappeared with cash registers that make change: an argument that never held sway with students who were not considering a future of "making change". So one "relevant" activity after another is seized upon:, and after each of these becomes obsolete the teacher is left wondering, "what is the point of all this?"

There is no end to that type of argument: it is both sterile and bankrupt. It is too specific to apply to many of our youth and quickly becomes outpaced by the progress of man: each "relevant" activity becoming irrelevant just months or years later. The very pace of sociocultural development betrays each of these activities to pointlessness.

Usefulness persists: not the usefulness of making change: the usefulness of our sociocultural heritage: the usefulness of mathematics to physics; of mathematics and physics to chemistry; of mathematics, physics and chemistry to biology. This is not an ephemeral sort of usefulness: it is fundamental to what it is to be human.

This is not limited to just mathematics and science: the same hierarchy of usefulness exists in all learning. It can be seen in the usefulness of grammar to writing; of writing and grammar to history; of grammar, writing and history to social policy; or their usefulness to writing a novel; etc. In a well organized educational community all of this heritage should come together as the connections between English, social studies, mathematics, science, art, music, etc. are made: the excitement of our students would rise ever higher: these connections are what they were born to make: these are what make us human.

This study was limited to exploring the dramatic impact of reintegrating a curriculum of study in mathematics and science so that the usefulness of learning was brought to bear in those realms; so that the usefulness of that learning was made visible; where the pedagogy used was appropriate to the sociocultural mediational tools being taught. The school that is experimenting with making these connections has made significant progress even with what has been done so far in just those realms. This will only multiply in effect as this approach is incorporated more effectively in and between more disciplines making an increasing number of connections at a geometric pace.

APPENDIX A: PHYSICS HONORS CURRICULUM

PHYSICS HONORS

Course Description

This course represents the first year in a comprehensive two year sequence of Algebra/Trigonometry based physics. The text used is *Physics* by Douglas C. Giancoli. This first course is comprised of Mechanics, which is studied for the first half of the year, Electricity and Magnetism, which is studied for most of the rest of the year and, finally, Fluids, to conclude the year.

The order of the topics taught during the two years has been geared to use and reinforce the mathematics that the students are studying. For this reason, the first year is geared towards reinforcing skills in algebra and requires no trigonometry. This is accomplished by restricting the first year course to problems that can be simplified to one-dimensional form. While vectors are introduced, they are only added and subtracted in one dimension at a time. This allows students to do about 90% of the problems presented in the portions the text being taught. Connections are also developed between the analysis of motion and graphical analysis, collision problems and the solving of systems of equations, etc.

The second year course begins with a brief review of that same material while introducing multi-dimensional problems, through the addition and subtraction of vectors in two and three dimensions. This is coordinated with the student's study of trigonometry.

Throughout both years, instruction will be carried out using a social constructivist approach. New concepts, techniques and approaches will be presented to the students at the start of class. Students will then be involved in problem-solving activities on an individual, small group and large group basis for most of the class. Through a large degree of teacher-student and student-student interaction students will be helped in constructing their own deep understanding of physics. This will include the ability to ability to read and understand problems, break them down into their component parts and then create and present solutions.

These same skills will be developed with activities in the physics laboratory. In that case, problem solving will be done in real time with hands-on problems. Much of the work done in the laboratory will include the gathering of data through PASCO electronic sensors. Those data will be configured by the students using the PASCO software and then analyzed using that software as well as a number of compatible programs, including Word and Excel. Through this process both analytical techniques as well as technological capability will be developed.

Students who have successfully completed this course should move onto Physics AP B. They will take the Physics AP B examination at the end of that course.

Course Objectives

1.	**Objectives**	**NJCCCS**
2.	Define and contrast position, distance and speed.	5.7A
3.	Use an inquiry approach to construct new understanding.	5.1A, 5.1B
4.	Read and interpret “word problems”.	5.1B
5.	Use algebraic techniques to solve for unknown values.	5.3A, 5.3C
6.	Solve literal equations.	5.3C
7.	Participate productively in large group discussion, inquiry and problem solving.	5.1A, 5.1B
8.	Participate productively in small group discussion, inquiry and problem solving.	5.1A, 5.1B
9.	Solve problems involving the relationship between position, distance and speed.	5.7A, 5.1B, 5.3C
10.	Compare and contrast speed vs. velocity as well as distance vs. displacement.	5.7A
11.	Define acceleration as the change in velocity over time.	5.7A
12.	Use motion diagrams to analyze problems.	5.7A, 5.1B
13.	Develop the kinematics equations that give the relationship between displacement, velocity and acceleration.	5.3B, 5.3C, 5.7A,
14.	Employ kinematics equations to solve problems for one-dimensional motion with constant acceleration	5.3C, 5.1B, 5.7A
15.	Conduct dimensional analysis.	5.1B
16.	Compare and contrast the approaches of Galileo and Aristotle.	5.2A, 5.2B, 5.7A
17.	Use hypothetico-deductive reasoning to develop and test predictions.	5.1A, 5.1B
18.	Obtain data from an experiment.	5.1A, 5.1B
19.	Use conventional laboratory equipment such as stopwatches, balances, etc.	5.1A, 5.1B
20.	Record and look for patterns in data.	5.1A, 5.1B

21.	Construct a graph with correctly formatted and labeled axes.	5.3D
22.	Graph data.	5.1B, 5.3D
23.	Analyze and interpret graphical data.	5.1B, 5.3D
24.	Discuss the historical impact of Galileo and his persecution by the church.	5.2A, 5.2B
25.	Define and apply Newton's Laws of motion.	5.7A
26.	Draw free body diagrams.	5.7A
27.	Contrast mass, force, and weight.	5.7A
28.	Use computerized laboratory equipment such as that provided by Pasco.	5.1B, 5.3D
29.	Construct free-body diagram for various physical systems to determine the forces on and the acceleration of the systems, for both rectilinear and uniform circular motion.	5.7A
30.	Use scientific notation.	5.1B
31.	Determine the gravitational force between massive objects.	5.7A
32.	Determine the work done on a physical system when the net force acting on it and its displacement are known.	5.7B
33.	Use energy bar charts to solve problems.	5.1B
34.	Employ the work/energy theorem to determine the motion of an object.	5.1B
35.	Define and contrast kinetic and potential energy and distinguish between different forms of potential energy.	5.7B
36.	Recognize when total mechanical energy is and is not conserved.	Beyond core standards
37.	Employ energy conservation to determine the position and motion of an object.	Beyond core standards
38.	Determine the impulse on a physical system when the forces on the system, and the time interval these forces act, are known.	Beyond core standards
39.	Use the impulse/momentum relation to determine the motion of a physical system	Beyond core standards
40.	Use momentum bar charts.	Beyond core standards
41.	Define and contrast elastic and inelastic collisions.	Beyond core standards

42.	Solve simultaneous equations.	5.3C
43.	Employ momentum conservation to determine the outcomes of collisions between the elements of the physical system.	Beyond core standards
44.	State the two types of electric charge, their sources, and how they interact.	5.7.A, 5.6A
45.	Define and contrast insulators and conductors.	Beyond core standards
46.	Describe the process of charging by conduction and induction.	Beyond core standards
47.	Employ Coulomb's Law to determine the electrostatic forces between two or more electric charges.	Beyond core standards
48.	Use and understand the appropriate prefixes: pico; nano; micro; milli; centi; kilo; and mega.	5.1A
49.	Define an electric field, and contrast it with electrostatic force.	Beyond core standards
50.	Construct electric field lines for various charge distributions in both homework and laboratory exercises.	Beyond core standards
51.	Define electrostatic potential, and potential difference.	Beyond core standards
52.	Use electronic laboratory equipment including voltmeters, ammeters, power supplies, etc.	5.1B
53.	Calculate the potential at points in the vicinity of one or more electric charges, and determine the work done by an electric field to move a test charge from one point to another.	Beyond core standards
54.	Construct equipotential lines for various charge distributions in both homework and laboratory exercises.	Beyond core standards
55.	Determine the capacitance of a parallel plate capacitor with, or without a dielectric, given the charge on plates, and the voltage across them.	Beyond core standards
56.	Define and contrast voltage, current, resistance.	Beyond core standards
57.	Employ Ohm's Law to determine the voltage, current, and resistance of series and parallel DC circuits in both homework and laboratory exercises.	Beyond core standards
58.	Determine the resistance of a DC circuit element when its composition, dimensions, and temperature are known.	Beyond core standards

59.	Calculate the power generated and dissipated by various DC circuit elements when current, voltage, and resistance are known.	Beyond core standards
60.	Determine the voltage and the charge on capacitors connected in series and in parallel combinations in a complete DC circuit.	Beyond core standards
61.	Determine the emf of a power supply in a DC circuit that has an internal resistance.	Beyond core standards
62.	Map magnetic field lines in the vicinity of one or more magnets.	Beyond core standards
63.	State how the direction of the magnetic field is determined for fields generated by ferromagnetic materials, and electric currents.	5.7A
64.	Map magnetic field lines in the vicinity of electric current.	Beyond core standards
65.	Calculate the strength of the magnetic field at a point in the vicinity of a straight wire or solenoid, and their directions using the right-hand rule.	Beyond core standards
66.	Determine the magnitude and the direction of force on an electric charge moving perpendicular to a uniform magnetic field.	Beyond core standards
67.	Calculate the magnitude and direction of force between two current carrying wires.	Beyond core standards
68.	Define magnetic flux through a surface.	Beyond core standards
69.	Employ Faraday's Law to determine the emf around a closed loop of wire when the flux changes due to change in field strength, or the orientation or size of the closed loop.	Beyond core standards
70.	Explain the operation of motors, generators and galvanometers and their development with respect to Faraday's work.	5.4B
71.	Explain how transformers work in AC circuits, and how they are advantageous in transmitting currents over long distance.	5.4B
72.	Define a fluid as being either a gas or liquid.	Beyond core standards
73.	Apply the relationship between density, volume and mass.	Beyond core standards
74.	Apply the relationship between density and specific gravity.	Beyond core standards
75.	Apply the relationship between force, applied area and pressure.	Beyond core standards

76.	Differentiate between absolute and gauge pressure.	Beyond core standards
77.	Determine the pressure at a given depth in a fluid.	Beyond core standards
78.	Determine the apparent weight of an object in a fluid.	Beyond core standards
79.	Apply Pascal's principle to create simple machines.	Beyond core standards
80.	Develop an experiment to test a theory.	5.1A, 5.1B
81.	Conduct an experiment to test a theory.	5.1B
82.	Exercise proper safety precautions when conducting experiments.	5.1C
83.	Properly use significant figures in calculations.	5.3D
84.	Estimate the error of actual measurement and recognize the importance of error calculations in science.	5.1A
85.	Share responsibilities in conducting experiments and collaborate to get the best results.	5.1A
86.	Share information and techniques with other groups doing related studies in order to work more efficiently.	5.1A
87.	Evaluate the results of experimental investigations.	5.1A, 5.3D

Course Content Outline

1. One- Dimensional Kinematics

   a. Motion in one dimension

   b. Vectors vs. scalars

   c. Displacement vs. Distance

   d. Velocity vs. Speed

   e. $x = x_0 + v_0t + ½ at^2$

   f. $v = v_0 + at$

   g. $v^2 = v_0^2 + 2 a \Delta x$

2. Dynamics
    a. Aristotelian World View
    b. Galilean view
    c. Newton's Laws
    d. Free body Diagrams
    e. The independence of parallel and perpendicular forces
    f. Gravity near the earth's surface and "g"
    g. Mass versus weight
    h. The use of $\Sigma F = ma$ and free body diagrams to solve problems
    i. Friction force – solving problems involving the interaction of horizontal and vertical forces
3. Circular Motion
    a. Net force required for circular motion equals mv^2/r
    b. Application of Free Body diagrams and Newton's Laws to circular motion
    c. Universal gravitation
    d. Satellites and 'weightless"
    e. Kepler's Laws and Newton's Synthesis
4. Linear Momentum
    a. Momentum and its relation to force
    b. Conservation of momentum
    c. Collisions and Impulse

d. Solving problems using the conservation of energy and momentum in collisions
e. Elastic collisions in one dimension
f. Inelastic collisions in one dimension

5. Work and Energy
    a. Work done by a constant force.
    b. Kinetic Energy and the Work-Energy Principle
    c. Gravitational Potential Energy
    d. Elastic Potential Energy
    e. Internal Energy and Joule's Principle
    f. Conservative and non-conservative forces
    g. Problem solving with the Principle of Conservation of Energy.

6. Electric Charge and Electric Field
    a. Electric charges and its conservation
    b. Interactions of charges
    c. Induced charges; the electroscope
    d. Coulomb's Law
    e. Electric field

7. Electric Potential
    a. Electric potential and potential difference
    b. Relation between electric potential and field
    c. Equipotential lines

   d. Capacitance
   e. Dielectrics
   f. Storage of Electric energy

8. Electric Currents
   a. The electric battery
   b. Electric current
   c. Ohm’s and Kirchoff’s Laws
   d. Resistivity
   e. Superconductivity
   f. Joule’s Law and Electric Power
   g. Alternating current
   h. Power in household circuits

9. DC Circuits
   a. Resistors in series and in parallel
   b. EMF and terminal voltage
   c. Kirchoff’s Rules: the conservation of charge and of energy
   d. EMF’s in series and in parallel
   e. Circuits with capacitors in series and in parallel
   f. Circuits with a resistor and a capacitor

10. Magnetism
   a. Magnets and magnetic fields
   b. Electric currents produce magnetic fields
   c. Force on an electric current in a magnetic field

d. Motion of the charged particle in a magnetic field (Lorenz force)

e. Magnetic field due to a straight wire

f. Force between parallel wires

11. Electromagnetic Induction

a. Induced EMF

b. Faraday's Law

c. EMF induced in a moving conductor

d. Changing magnetic flux produces and electric field

e. Electric generators

f. Conversion of mechanical to electric energy as the underlying basis to modern technological society

g. Electromagnetic waves

12. Fluid Statics

a. Density and Specific Gravity

b. Pressure in Fluids

c. Atmospheric and Gauge Pressure

d. Pascal's Principle

e. Barometers

f. Buoyancy and Archimedes's Principle

Course Assessment

Formative assessments are done by the teacher in order to assure that the students understand the material that has been taught. They create a feedback loop between the students and the teacher so that misunderstandings can be corrected and instruction modified to optimize the learning environment.

These formative assessments occur during class and can be divided into two categories. The first category is ungraded and consists of student participation, student responses to questions, observed student-student interactions and homework completion

The second type of formative assessment is graded and consists of quizzes, based on previously discussed homework assignments; quests, which are full period assessments that check a broader set of problems at the same level of difficulty as quizzes; and reading quizzes, which check to see if students have been completing reading assignments. Altogether these assessments represent about 20 - 30 % of the marking period grade.

Summative assessments take the form of chapter tests, midterms and finals. These are all given in the same form as the AP exam; half multiple choice and half free response. The multiple choice questions are conceptual in nature while the free response section involves solving multi-step problems; often taken from prior AP exams. Chapter tests comprise about 50 - 60% of each marking period grade. The midterm and final exam each represent 10% of the full year grade; combined they equal a marking period grade.

The intention is for identical summative assessments to be given to all the students in the course on the same day, regardless of their teacher. This is to encourage students to study together in groups, with or without a teacher, to advance their skill and understanding..

Laboratory work is graded and typically represents about 20% of each marking period grade. The grade is divided evenly between the work done in the lab, based on teacher observation, and the lab report.

Methodology

Lecture

Use of this method will be limited to the introduction of new topics and will be of short duration, no more than 10 minutes in one class period. Concepts will generally be developed through class discussion with the teacher serving the role of moderator and recorder rather than lecturer. Many classes will not include this component at all. The students will need to use their visual, listening, writing skills and organization skills to benefit from this part of the course. Students will be required to keep complete and organized notebooks

Large group Problem Solving and Discussion Sessions

The teacher will lead these sessions where students will actively participate in raising questions, answering questions and expanding upon topics. The entire class will work together to solve complex problems which test their understanding of the ideas being developed. The teacher will coordinate these sessions to ensure that all the students participate. This is vital in that this gives each student the opportunity to expand their understanding. By increasing the

Zone of Proximal Development (ZPD) for all the students, they will be able to quickly advance their understanding.

Small Group Problem Solving Sessions

In these sessions a few problems will be given to the entire class and they will work in groups of 2 to 4 students to solve them. Once most of the problems have been solved, each group will present a solution to one of the problems to the rest of the class. Disputes and different approaches will be discussed in the Large Group format with the class taking the lead in determining the best approach. The teacher serves to chair the discussion. Once again this activity is designed to allow the students to quickly learn in an environment where their ZPD has been expanded.

Hands-On Activities / Laboratory / Discovery

Students need to not only solve problems analytically but also apply those solutions to real hands-on problems. These sessions are generally, but not exclusively, held in the physics laboratory and involve two to four students working together. The students will be asked to conduct experiments that either apply or develop new understandings. These will not be cookbook experiments, where the students simply walk through a procedure. Rather, these experiments involve gathering data and making analyses where the results are unknown to them, and sometimes even to the instructor.

These labs will use actual physical apparatus, often with electronic probes to gather data and computers to conduct analysis. Whenever possible, they will be performed towards the beginning of each unit, affording the student the experience of discovering the concepts before they are formally taught by the instructor. One objective of each lab exercise is for each student to analyze their data using data and error analysis techniques in order to judge the accuracy and meaning of their results.

Reading

Students will be encouraged to develop the self-confidence and techniques required to learn directly from the text. The techniques needed to accomplish that will be discussed in class and reviewed from time to time. Readings will be assigned to either introduce or reinforce topics. In this way, classroom time is not spent reviewing every fact and detail for which the students will be responsible. Students will then be better prepared to participate and engage in active classroom discussion. The skill of being able to read and understand a text is so critical that great effort will be made to encourage students to develop it. In this vein, reading quizzes will be given from time to time to determine that students are completing their reading assignments.

Homework problems

Problems will be assigned every night so that students can apply the learning that was done during class that day. This will be checked by periodic homework quizzes that will be given the day after the assignment was due. In that way, student who made an honest effort but need to ask questions in class to reach a correct solution are not penalized. The homework quizzes are designed to test that students are learning how to do these problems. This contrasts with collecting assignments, which can lead to copying rather than understanding.

<u>Field Trips</u>

Appropriate trips out of the school environment are an excellent way to show students that what they learn in classroom definitely relates to the word at large. Students are given a chance to see how ideas develop into real life situations and have real-life applications.

<u>Resources</u>

<u>Physics:</u> <u>Principles with Applications</u>

Douglas C. Giancoli

ISBN: 0136119719

Format: Hardcover, 1096pp

Pub. Date: August 1997

Publisher: Prentice Hall

Edition Description: 5^{TH}

This best-selling algebra-based physics book has been widely known for its carefully crafted exposition, strong biological applications, and high degree of accuracy and precision. The Fifth Edition maintains these strengths and brings a conceptual emphasis and real-world flavor to the examples, problems, and art program. In addition, the new edition features an unparalleled suite of media and on-line resources to enhance the physics classroom.

Additional Textbook: Beiser, A., Physics, 5^{th} edition, Addison Wesley 1991

Laboratory Software: PASCO

APPENDIX B: AP PHYSICS B CURRICULUM

AP PHYSICS B

Course Description

AP Physics B is the second of a two-year sequence that is designed to prepare students to take the AP Physics B examination. It begins by integrating the use of trigonometric functions into the Physics Honors topics of mechanics and electricity & magnetism. This allows students to solve problems with vectors that are oriented at arbitrary angles; rather than just parallel or perpendicular to one another. The course then addresses the topics of waves; sound; thermodynamics; geometrical optics; wave optics; as well as introductory atomic & nuclear physics.

This course emphasizes problem solving in the context of the principles of physical laws and principles; as well as the ability to apply that knowledge and skill to phenomenon in either an experimental or theoretical setting. Great attention is given to strengthening and reinforcing the natural connections between the sciences and with mathematics.

Proper preparation to take this course includes the completion of Physics Honors and Algebra I. While it is best if Geometry is completed prior to the start of this course; it is possible to take it in parallel if the student is able to commit additional time and effort.

Students will be involved in problem-solving activities on an individual, small group and large group basis. Through this process the ability to read and understand problems, break them down into their component parts and then create and present solutions will be developed.

These same skills will be developed with activities in the physics laboratory. In that case, problem solving will be done in real time with hands-on problems. Much of the work done in the laboratory will include the gathering of data through PASCO electronic sensors. Those data will be configured by the students using the PASCO software and then analyzed using that software as well as a number of compatible programs, including Word and Excel. Through this process both analytical techniques as well as technological capability will be developed.

Course Objectives

Course objectives that were previously achieved in the prerequisite course, Physics Honors, are not duplicated below. However, the reviews of specific categories of content from the prior course are included below: accomplishing those reviews must be considered as objectives of this course. However, process objectives, such as laboratory techniques, group discussion, etc. which were noted in the objectives for Physics Honors are not repeated below as those will not require explicit review: they will be reviewed implicitly through their use.

	Objectives	**NJCCCS**
1.	Review the kinematics from Physics Honors (see that curriculum).	5.7A
2.	Decompose vectors into perpendicular components.	Beyond Core Standards
3.	Compose vectors from its perpendicular components.	Beyond Core Standards

4.	Add or subtract multiple vectors, oriented at arbitrary angles, using either graphical or analytical methods.	Beyond Core Standards
5.	Review dynamics from Physics Honors (see that curriculum).	5.7A
6.	Determine the net force due to multiple forces at arbitrary angles.	5.7A
7.	Determine the acceleration of an object due to multiple forces acting on it at arbitrary angles.	5.7A
8.	Review energy from Physics Honors (see that curriculum).	5.7B
9.	Determine the work done on a system when a net force acts on it at an arbitrary angle to its displacement.	5.7B
10.	Employ the work/energy theorem to determine the motion of a physical system in two dimensions.	5.7B
11.	Apply the concept of impulse to solve problems in two dimensions.	5.7A
12.	Solve problems involving perfectly inelastic collisions of objects whose velocities are at arbitrary angles.	5.7A
13.	Solve problems involving perfectly elastic collisions of objects whose velocities are at arbitrary angles.	5.7A
14.	Solve problems involving inelastic collisions of objects whose velocities are at arbitrary angles.	5.7A
15.	Review the fluid statics from Physics Honors (see that curriculum).	Beyond Core Standards
16.	Use Bernoulli’s Principle to describe the relationship between pressure, height and fluid velocity.	Beyond Core Standards
17.	Apply Bernoulli’s Principle to solve problems involving the relationship between pressure, height and fluid velocity.	Beyond Core Standards
18.	Use the concept of torque to solve for the static equilibrium of a system.	Beyond Core Standards
19.	Define the criteria of an oscillating body exhibiting simple harmonic motion.	5.7B
20.	Determine the energy, position, speed, acceleration, frequency, and period of a physical system.	5.7A, 5.7B
21.	Define and contrast longitudinal and transverse waves, and give at least one example of each.	Beyond Core Standards
22.	Use ray diagrams to solve problems in geometric optics.	Beyond Core Standards
23.	Define reflection, refraction, diffraction, and interference	Beyond Core Standards
24.	Determine the overtone series for vibrating strings and pipes.	Beyond Core Standards

25.	Determine the apparent frequency of a sound source moving with respect to an observer.	Beyond Core Standards
26.	Determine the beat frequency of a system of two resonators of different frequencies.	Beyond Core Standards
27.	Employ the kinetic theory of matter to explain temperature, thermal expansion, heat transfer, and the attributes of an ideal gas.	Beyond Core Standards
28.	Determine the expansion of materials of known initial dimensions when they undergo a temperature change.	Beyond Core Standards
29.	Employ the ideal gas law to determine the pressure, volume, and temperature of an ideal gas.	Beyond Core Standards
30.	Define and contrast heat, temperature, and internal energy.	Beyond Core Standards
31.	Describe James Joule's determination of the mechanical equivalent of heat, and its numerical value.	5.2B
32.	Employ energy conservation to determine the specific and latent heats of various substances Define and contrast conduction, convection, and radiation as methods of heat transfer.	Beyond Core Standards
33.	Calculate the rate of heat transfer between two objects for both conduction and radiation.	Beyond Core Standards
34.	Define and contrast isobaric, isochoric, isothermal, and adiabatic thermal processes.	Beyond Core Standards
35.	Employ the first law of thermodynamics to determine the temperature, pressure, and volume of an ideal gas that undergoes isobaric, isochoric, isothermal, and adiabatic processes.	Beyond Core Standards
36.	Use the second law of thermodynamics to explain why no heat engine can be100% efficient.	5.7B
37.	Calculate the efficiencies of various heat engines when the intake and exhaust temperature are known.	Beyond Core Standards
38.	Describe how the increase in entropy affects all physical phenomena.	5.7B
39.	Review electrostatics from Physics Honors (see that curriculum).	5.7A
40.	Employ Coulomb's Law to determine the electrostatic forces between three or more electric charges located at arbitrary angles to one another.	Beyond Core Standards
41.	Add electric fields which are oriented at arbitrary angles to one another.	Beyond Core Standards
42.	Review magnetism from Physics Honors (see that curriculum).	Beyond Core Standards
43.	Add magnetic fields which are oriented at arbitrary angles.	Beyond Core Standards

44.	Determine the force on a current carrying wire oriented at an arbitrary angle to a magnetic field.	Beyond Core Standards
45.	Determine the force on a charged object whose velocity is at an arbitrary angle to a magnetic field.	Beyond Core Standards
46.	Determine the force current carrying wires oriented at an arbitrary angle to each other.	Beyond Core Standards
47.	Identify the complete electromagnetic spectrum and be able to list its components in order of frequency.	Beyond Core Standards
48.	Relate the speed of wave with its frequency and wavelength.	Beyond Core Standards
49.	Relate a transparent material's index of refraction to the speed of light in the material.	Beyond Core Standards
50.	Determine the position, size, and type of images generated by both spherical mirrors and thin lenses by both ray tracing and calculation.	Beyond Core Standards
51.	Use Huygen's Principle to explain the diffraction of light waves.	Beyond Core Standards
52.	Explain Young's Double Slit experiment and its implications regarding the wave nature of light.	5.1A, 5.2B
53.	Use Young's experimental set up to determine the wavelength of light in both homework and laboratory exercises.	Beyond Core Standards
54.	Explain the principle of dispersion.	Beyond Core Standards
55.	Determine the width of the central maximum formed from single slit diffraction.	Beyond Core Standards
56.	Use a diffraction grating to determine the wavelength of light.	5.1B
57.	Determine the thicknesses of thin films and air wedges from knowing the wavelength of the reflected light.	5.1B
58.	Determine the intensity of light that is passed through one or more polarizing filters of known orientation.	Beyond Core Standards
59.	Explain how Plank's quantum hypothesis explains the spectrum of black body radiation.	5.1B

Course Outline

1. **Kinematics**

   a. Decomposition of vectors

   b. Composition of vectors

c. Review - Motion in one dimension

d. Motion in two dimensions (Independence of perpendicular components)

e. Displacement in two dimensions

f. Velocity in two dimensions

g. Acceleration in two dimensions

h. Projectile motion

i. Review - Uniform circular motion

j. Review - Motion of the satellites

2. Dynamics

a. Review - Newton's Laws

b. Free body diagrams in two or three dimensions

c. Determining the net force due to forces acting at arbitrary angles

d. Decomposing forces into perpendicular components

e. Friction when an applied force is at an arbitrary angle

f. Net force due to a banked curve

g. Review - Elastic force

h. Review - The Law of Universal Gravitation

3. Rotational Motion

a. Torque

b. Static equilibrium due to equal and opposite torques

4. Impulse and Momentum

a. Review - Impulse and momentum

b. The effect of impulse at an arbitrary angle to initial velocity

c. Review – Collisions: Perfectly elastic, perfectly inelastic, inelastic

d. Perfectly inelastic collisions of objects moving in arbitrary directions

e. Perfectly elastic collisions of objects moving in arbitrary directions

f. Inelastic collisions of objects moving in arbitrary directions

g. Conservation of momentum with objects moving in arbitrary directions

5. Energy

a. Review – Work, Energy and Power

b. Work when force and displacement are at arbitrary angles

6. Thermodynamics

a. Ideal Gas Law

b. Kinetic Model

c. Zeroth Law of Thermodynamics (Thermometry)

d. First Law of Thermodynamics (Energy Conservation)

e. Second Law of Thermodynamics (Entropy)

f. P-V diagrams

g. Mechanical Equivalent of Heat

h. Specific and Latent Heat (Calorimetry)

i. Heat transfer and thermal expansion

7. Electricity

a. Review - Electric charges and their interaction

b. Review - Electric field intensity

c. Review - Potential and Voltage

d. Review - Capacitance and Capacitors

e. Adding electric fields at arbitrary angles

f. Motion of a charged particle traveling at an angle to an electric field

g. Review - Current, Voltage, Resistance

h. Review - Ohm's and Kirchoff's Laws

i. Review - Joule's Law

j. Review - Electric Power

8. Magnetism

a. Review - Magnetic Field

b. Review - Magnetic field due to a current carrying wire (Ampere's Law)

c. Review – Force on current carrying wires perpendicular to magnetic fields

d. Force on current carrying wires at arbitrary angles to magnetic fields

e. Review – Force between parallel current carrying wires

f. Force on current carrying wires at arbitrary angles to one another

g. Review – Force on a charge moving perpendicular to a magnetic field

h. Force on a charge with a velocity at an arbitrary angle to a magnetic field

i. Review - Motion of a charged particle in a magnetic field (Lorenz force)

j. Review - Electromagnetic Induction

k. Self-Induction

l. Addition of magnetic fields at arbitrary angles

9. Oscillations and Waves

a. Simple Harmonic Motion

b. Oscillation and Energy Transformation

c. Resonance

d. Mechanical Waves (Longitudinal and Transverse)

e. Waves Interference and Diffraction

10. Waves and Optics

a. Properties of traveling waves

b. Properties of standing waves

c. Doppler effect

d. Superposition (Interference)

e. Interference and diffraction

f. Dispersion of light and the electromagnetic spectrum

g. Reflection and Refraction

h. Mirrors

i. Lenses

11. Atomic and Nuclear Physics

a. Alpha particles scattering and the Rutherford model of the atom

b. Photons and the photoelectric effect

c. Bohr model of the atom (including energy levels)

d. Wave-particle duality

e. Radioactivity and half-life

f. Nuclear reactions

(a) Conservation of mass number

(b) Conservation of charge

(c) Mass-energy equivalence

Course Assessment

Formative assessments are done by the teacher in order to assure that the students understand the material that has been taught. They create a feedback loop between the students and the teacher so that misunderstandings can be corrected and instruction modified to optimize the learning environment.

These formative assessments occur during class and can be divided into two categories. The first category is ungraded and consists of student participation, student responses to questions, observed student-student interactions and homework completion.

The second type of formative assessment is graded and consists of quizzes, based on previously discussed homework assignments; quests, which are full period assessments that check a broader set of problems at the same level of difficulty as quizzes; and reading quizzes, which check to see if students have been completing reading assignments. Altogether these assessments represent about 20 - 30 % of the marking period grade.

Summative assessments take the form of chapter tests, midterms and finals. These are all given in the same form as the AP exam; half multiple choice and half free response. The multiple choice questions are conceptual in nature while the free response section involves solving multi-step problems; often taken from prior AP exams. Chapter tests comprise about 50 - 60% of each marking period grade. The midterm and final exam each represent 10% of the full year grade; combined they equal a marking period grade.

The intention is for identical summative assessments to be given to all the students in the course on the same day, regardless of their teacher. This is to encourage students to study together in groups, with or without a teacher, to advance their skill and understanding.

Laboratory work is graded and typically represents about 20% of each marking period grade. The grade is divided evenly between the work done in the lab, based on teacher observation, and the lab report.

Methodology

Lecture

Use of this method will be limited to the introduction of new topics and will be of short duration, no more than 10 minutes in one class period. Concepts will generally be developed through class discussion with the teacher serving the role of moderator and recorder rather than lecturer. Many classes will not include this component at all. The students will need to use their visual, listening, writing skills and organization skills to benefit from this part of the course. Students will be required to keep complete and organized notebooks

Large group Problem Solving and Discussion Sessions

The teacher will lead these sessions where students will actively participate in raising questions, answering questions and expanding upon topics. The entire class will work together to solve complex problems which test their understanding of the ideas being developed. The teacher will coordinate these sessions to ensure that all the students participate. This is vital in that this gives each student the opportunity to expand their understanding. By increasing the

Zone of Proximal Development (ZPD) for all the students, they will be able to quickly advance their understanding.

Small Group Problem Solving Sessions

In these sessions a few problems will be given to the entire class and they will work in groups of 2 to 4 students to solve them. Once most of the problems have been solved, each group will present a solution to one of the problems to the rest of the class. Disputes and different approaches will be discussed in the Large Group format with the class taking the lead in determining the best approach. The teacher serves to chair the discussion. Once again this activity is designed to allow the students to quickly learn in an environment where their ZPD has been expanded.

Hands-On Activities / Laboratory / Discovery

Students need to not only solve problems analytically but also apply those solutions to real hands-on problems. These sessions are generally, but not exclusively, held in the physics laboratory and involve two to four students working together. The students will be asked to conduct experiments that either apply or develop new understandings. These will not be cookbook experiments, where the students simply walk through a procedure. Rather, these experiments involve gathering data and making analyses where the results are unknown to them, and sometimes even to the instructor.

These labs will use actual physical apparatus, often with electronic probes to gather data and computers to conduct analysis. Whenever possible, they will be performed towards the beginning of each unit, affording the student the experience of discovering the concepts before they are formally taught by the instructor. One objective of each lab exercise is for each student to analyze their data using data and error analysis techniques in order to judge the accuracy and meaning of their results.

Reading

Students will be encouraged to develop the self-confidence and techniques required to learn directly from the text. The techniques needed to accomplish that will be discussed in class and reviewed from time to time. Readings will be assigned to either introduce or reinforce topics. In this way, classroom time is not spent reviewing every fact and detail for which the students will be responsible. Students will then be better prepared to participate and engage in active classroom discussion. The skill of being able to read and understand a text is so critical that great effort will be made to encourage students to develop it. In this vein, reading quizzes will be given from time to time to determine that students are completing their reading assignments.

Homework problems

Problems will be assigned every night so that students can apply the learning that was done during class that day. This will be checked by periodic homework quizzes that will be given the day after the assignment was due. In that way, student who made an honest effort but need to ask questions in class to reach a correct solution are not penalized. The homework quizzes are designed to test that students are learning how to do these problems. This contrasts with collecting assignments, which can lead to copying rather than understanding.

Field Trips

Appropriate trips out of the school environment are an excellent way to show students that what they learn in classroom definitely relates to the word at large. Students are given a chance to see how ideas develop into real life situations and have real-life applications.

Resources

Physics: Principles with Applications

Douglas C. Giancoli

ISBN: 0136119719

Format: Hardcover, 1096pp

Pub. Date: August 1997

Publisher: Prentice Hall

Edition Description: 5^{TH}

This best-selling algebra-based physics book has been widely known for its carefully crafted exposition, strong biological applications, and high degree of accuracy and precision. The Fifth Edition maintains these strengths and brings a conceptual emphasis and real-world flavor to the examples, problems, and art program. In addition, the new edition features an unparalleled suite of media and on-line resources to enhance the physics classroom.

Additional Textbook: Beiser, A., Physics, 5^{th} edition, Addison Wesley 1991

Laboratory Software: PASCO

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