

Liberal Education in a Technological Age: The Education of a Scientifically-Literate Society

**Final Report to the National Science Foundation
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I. INTRODUCTION

The United States will need a scientifically and technologically literate citizenry to cope with the accelerating pace of change and to set appropriate educational, industrial, and national priorities. Only an educated public can evaluate competing claims about risk and benefit and make reasonable choices and decisions about technical issues, whether it is to fund research at the national level or to evaluate the credibility of evidence presented in a court of law. However, most students in Universities do not choose to major in science- or technology-related fields. At the University of Rochester, 72% of undergraduates major in the Humanities and Social Sciences.

Many institutions have attempted to introduce non-science majors to the ways in which science and technology function. These science courses for non-majors are usually based on one of two schemes. One is "show them everything", and the other is "show them what they think they need."

The "show them everything" scheme attempts to show students everything about a field of science in one or possibly two semesters. For example, a non-major taking a physics course is bombarded in one semester with Classical Mechanics, Electricity and Magnetism, Relativity, and Quantum Mechanics, all without significant mathematics. The claim is that students appreciate the scientific method and the beauty of science even if they cannot do science by the end of the course. However, it is impossible for any student to sort out the amount of information presented in a one-semester of "Show them everything" course. Even science majors take many semesters to make sense of it all, and they are motivated to pursue the area even in the face of confusion. The non-major never has the time to sort out the mass of material and have it make sense.

The "show them what they think they need" approach usually offers courses that are tightly focused on topics of interest to students. "Physics of hi-fi," "Chemistry in the Environment," or other topical courses are examples of this approach. In such courses, students only see smatterings of extremely complicated topics that are still debated among experts, and so are left with minimal understanding of the material. In both approaches, students achieve at best a declarative knowledge of the field rather than a functional one. They might be able to state isolated facts, but are not able to use the underlying theories to form new theories or to evaluate a new strategy as opposed to an old one.

To improve the quality of the undergraduate education outside the major, the University of Rochester recently adopted a new requirement that all undergraduates must engage in three areas of focused study: one each in Humanities, Social Science, and Natural Science / Engineering / Mathematics. One area of focus will be the student's major, and students must elect a Cluster of three related courses in each of the two divisions outside the major. They must earn a C average in each cluster. Students of Engineering, because of the already strict requirements of the

ABET-accredited curricula, will have to complete only one Cluster in Humanities or Social Science, and are required to take another two courses in those areas by their Departments.

This new curriculum requires every Humanities and Social Science major to take at least three related courses in the Natural Science / Engineering / Mathematics area. It presented the University with an opportunity to significantly revise and improve the experience of non-majors and to change the way the sciences, engineering, and mathematics are taught to non-science majors. A request for proposals from the National Science Foundation aimed at institution-wide reform of undergraduate science education brought together a cross-disciplinary group of Natural Science / Engineering / Mathematics faculty to explore the development of a new cluster of science courses. Our proposal to develop a new cluster of science courses was accepted by the National Science foundation, and funding was approved in 1997.

This report summarizes the work we have carried out as part of this program and the impact that funding of this project has had on the undergraduate education at the University of Rochester. In Section II the courses that were developed as part of this program are described. A summary of the assessment of our efforts is provided in Section III. The general impact of this project on undergraduate education at the University of Rochester is described in Section IV. Our conclusions are summarized in Section V.

II. COURSE DEVELOPMENT

The courses that were developed as part of this program apply an inquiry-based approach, which exposes students to the scientific method. These courses address the larger view of science by exploring what constitutes a scientific theory, by providing students with the opportunity to engage in scientific hypothesis testing in the laboratory, and by examining the writings of scientists and their humanist contemporaries about the worldview that science provides. Rather than "show and tell," the courses focus on the process of discovery. This process is not only used to teach the basic principles of science, but also studies science from a historical perspective (Several major scientific concepts that provided radical challenges to accepted world views at the time they were proposed are used to illustrate the operation of the scientific method). The students are also exposed to the design process, specifically the process of determining the constraints and the optimization of the design. This is a topic to which even science majors are usually not exposed, but which clearly affects everyday life.

The courses that were developed as part of this program are described in the remainder of this Section.

IIa. Life's Devices: Mechanical design in biological & man-made structures

The course "*Life's Devices: Mechanical design in biological & man-made structures*" was developed by Professors Renato Perucchio and John Lambropoulos in the Department of Mechanical Engineering at the University of Rochester. The course was first taught in Fall 1997, and has been taught each fall since then. The course is aimed at students, mostly freshmen or sophomores, having an interest in technology in general but not necessarily majoring in engineering.

It is clear to many faculty and educators that a scientifically literate society must be able to address and evaluate rationally the products of its technology, from nail-clippers to the space shuttle. Science becomes technology, and technology produces the devices of every-day life

through the process of design. Design is a fundamental part of all engineering curricula, and is currently often taught as a capstone course after the students have completed the entire math, physics, and engineering analysis courses. The goal of this course is to educate non-engineering students at UR about the process of design. What are the design constraints, how are these constraints implemented, which issues arise when designing a product, how are these issues resolved, and is creativity perhaps more important than technical expertise in successful design of products? Design is an open-ended, creative process in which there is no unique solution to a design problem. In fact, there may be many “correct” solutions, all of which may meet the design constraints. This is in contrast to the often held belief by non-science majors that in science there is always a single correct solution.

The fundamental technical content that the students learn in this course are the concepts of force and power, and how engineering structures are used to transmit these. In addition to this, the course focuses on other issues that the design process must address, such as economics, ethics, aesthetics, safety, and legal issues, and how these effects are evaluated when making design decisions and are implemented in the design of common appliances used in every-day life.

To motivate the students from the very beginning, design is discussed in the context of two areas in which all students have a very good intuitive understanding: the human and animal bodies, and man-made structures which humankind has been using over the centuries. To study the mechanical design of human-made structures, the students start by looking at simple devices used in antiquity for transmitting force and power for peaceful and war-like purposes such as water wheels, war ships, bows and arrows, aqueducts, domes, and buildings. The students then discuss the design process by examining common utensils, and discussing how design choices are made among different materials, functions, etc. When the students examine biological design, they discover how the size and function of many living

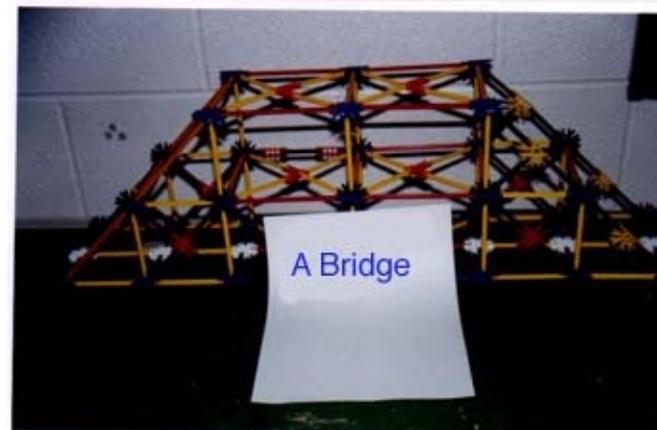
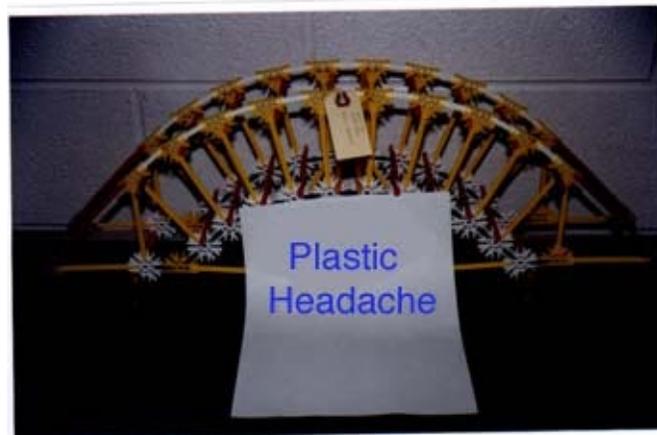


Figure 1. Examples of different designs of a truss bridge created by students enrolled in ME104Q, *Life's Devices*.

biological structures is related to their mechanical design for the transmission of force and power, and how the mechanical design of “small” organisms is fundamentally different from the design of “large” ones, although the physical principles are exactly the same in both cases. In this part of the course, the students also focus on the process of measurement, and how one can make excellent approximations of the dimensions of these biological structures by the process of estimation.

The students have to hand in design projects and reports from the very beginning of the course. Students are required to work in teams of two to three students in order to emphasize the value of coordination, exchange of ideas, and brainstorming. Each team is given a construction kit, consisting of about 1000 plastic Kinex pieces, for the design of three-dimensional structures such as towers, bridges, and domes. Kinex pieces are used, rather than for example balsa wood and glue, since Kinex hinges and beams all have equal strength. As a result, the success of each student team is not based on their dexterity in using glue, but rather on their skills conceiving and executing geometrical structural design in two and three dimensions. The Kinex beams and hinges can be very quickly snapped in and out of position, allowing many different designs to be explored in a short period of time. During the semester the following 7 projects are carried out:

1. Design of containers for storing and transporting inexpensive optical components.
2. Design, construction, and testing of a bridge (using Kinex sets).
3. Design, construction, and testing of an air-wing beam (using Kinex sets).
4. Raise an obelisk into place, using pre-1500 AD technology.
5. Design, construction, and testing of a bridge (using Kinex sets). Note: this is a repeat of project 2.
6. Design, construction, and testing of an air-wing beam (using Kinex sets). Note: this is a repeat of project 3.
7. Design of a life’s device ((i) Structure to help disabled people



Figure 2. Examples of different designs of an aircraft wing created by students enrolled in ME104Q, *Life’s Devices*.

into and out of a swimming pool, OR (ii) Portable seat/back support in benches, OR (iii) Inexpensive loft-bed for student dormitories)

For each project, each team hands in one agreed upon design solution. In addition, each student of the team is required to hand in a separate design report, which describes in detail the design process and the final design solution. Each design is tested to ensure it meets the design goals. Examples of different designs of a truss bridge are shown in Figure 1. Figure 2 shows examples of different designs of an aircraft wing.



Figure 3. Picture of the computerized classroom (B&L 407) constructed for the *Physics by Inquiry* course.

IIIb. *Physics by Inquiry*

The *Physics by Inquiry* course was developed by Professor Frank Wolfs of the Department of Physics and Astronomy. The goal of *Physics by Inquiry* is to provide the students with direct experience in the process of science. The design of this course was based on the belief that science can not be learned by reading, listening, memorizing and problem solving, but requires active mental engagement. Although most science courses for science majors are supplemented with required labs, even in those courses active engagement is rather limited. In most of our current science courses for non-science majors, the laboratory component is missing, and these courses often fail to provide the students with a scientific intuition and an appreciation for the scientific process.

Physics by Inquiry focuses on the scientific method. The students start from their own observations, develop basic scientific concepts, use and interpret different forms of scientific representations, and construct explanatory



Figure 4. *Physics by Inquiry* students hard at work in B&L 407.



Figure 5. *Physics by Inquiry* students hard at work in B&L 407, trying to carry out a motion in front of a motion sensor that is shown on a graph on their computer screen.



Figure 6. Inelastic collision between 2 *Physics by Inquiry* teaching assistants, using full soda cans as bumpers.

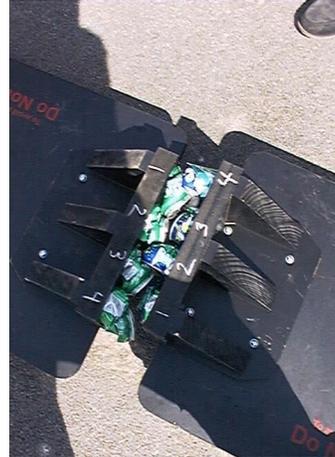


Figure 7. Results of an inelastic collision between two *Physics by Inquiry* students. The deformation of each can was measured in order to determine the correlation between deformation and loss of kinetic energy.

models with predictive capabilities. The students develop scientific reasoning skills and gain experience in relating scientific concepts, representations, and models to real-world phenomena. By providing a direct exposure to the scientific process, we hope to provide the students with a solid foundation for scientific literacy. Topics that are covered in this course are physics and astronomy.

To achieve the goal of active involvement, the course is taught in a computer-equipped classroom in which each student (or pair of students) has access to a computer and is able to carry out data analysis during lectures. Simple experiments are carried out by each student individually. More sophisticated experiments are carried out by the instructor, and the data collected are available to each student via the network. For example, complicated two-dimensional motion is videotaped and digitized for immediate analysis by the students.

The funds for the construction of the computer equipment for the computerized classroom were provided by the University. Figure 3 shows a photograph of the classroom (B&L 407) in the Department of Physics and Astronomy, which was constructed for the *Physics by Inquiry* course. Figures 4 and 5 show pictures of some of the *Physics by Inquiry* students at work during the “lecture” period. Most of the “lecture” period is devoted to hands-on experiments, which focus on various aspects of the scientific method. The students shown in Figures 4 and 5 are working on an experiment in which they are asked to carry out a motion in front of a motion sensor that describes the curve shown on their computer screen. This experiment is used to gain experience with scientific graphics, and with graphing motion in particular.

Some of the experiments carried out by the *Physics by Inquiry* students were carried out outside the classroom. Examples, include the following:

- Study of inelastic collisions between two carts. In these experiments the students experience inelastic collisions hands-on. The collisions between the two carts are videotaped in order to allow the extraction of the velocities before and after the collision, and the deformation of the bumpers of the carts is measured in order to look for a correlation between the deformation of the bumper and the loss of kinetic energy in the collision. Figures 6 and 7 show two pictures taken during these experiments.



Figure 8. The best performing *Physics by Inquiry* rocket.



Figure 9. One of the many other rockets designed and build by the *Physics by Inquiry* students.



Figure 10. *Physics by Inquiry* rocket survives a hard landing.



Figure 11. Two *Physics by Inquiry* students admire the way their rocket landed after reaching a height of 200 ft.

- Design, construction, and launching of rockets. In these experiments, the students design and build various water rockets, paying specifically attention to the aerodynamic properties of these rockets. The rockets are launched during the regular class period, and the launches are videotaped for later analysis. Using video analysis tools the students determine that the best performing rockets achieve speeds in excess of than 110 miles per hour on take off and reach altitudes of over 300 feet. Some pictures taken during these experiments are shown in Figures 8 – 11.

In the current academic year, *Physics by Inquiry* will be taught for the fourth time. Several new innovations were made during the summer and it is hoped that the experience gained with this inquiry-based approach to teaching can also be applied in a number of undergraduate courses for science majors.

IIc. *Clockwork to Chaos*

The *Clockwork to Chaos* course was developed by Prof. Ian Walmsley of the Institute of Optics and by Professor Daniel Albright of the Department of English, and is taught jointly by them. The intent of the course is to show the connectivity of knowledge across the broad spectrum of academic disciplines, from the purely symbolic to the completely representational, by introducing some of the major developments in physics, chemistry and biology that have shaped our world view, and how the consequences of that world view have been explored in literature, art and music. As an example, the ideas developed by Leibniz as the calculus of variations are illustrated in specific form by deriving Snell's Law of Refraction from Fermat's Principle. Leibniz' exaltation of minimization schemes to the level of a teleology --the mathematical, and therefore logical, extension of Occam's Razor -- are explored in the writings of Voltaire, particularly in *Candide*, and the untenable position of extending a physical or mathematical theory beyond its domain of validity is exposed.

The central themes of the course, which relies heavily on participation of the students via in-class discussions, are explored by extensive reading in both introductory science books (and in non-mathematical articles by the scientists who discovered some of the major ideas) and in literature. The students are evaluated by the preparation and execution of three projects and an essay, for each of which they develop a particular theme to greater depth, and which may encompass any area of human enquiry. Some examples are indicated by the presentation titles: The reversibility of time in physical equations, and Borges "A New Refutation of Time"; Ptolemy's epicycles, Fourier's series and Ligeti's tone poems: stochastic vs. regular time series; The futurist machine-music of Prokofiev, Russolo, Antheil and Mosolov: noise, technology and art. It is important to realize that the construction of these presentations requires extensive research on the part of the students, as well as a sorting of ideas -- in importance, chronology and logical sequence -- and therefore helps them to develop critical thinking outside the boundaries of a specific discipline, honing skills that are broadly applicable.

Students enrolled in this course will explore how scientists develop models, including the balance of inductive and deductive reasoning inherent in the classical scientific method, the nature of physical law and falsifiability, the grand ideas of physics (and some of chemistry and biology) from Newtonian mechanics to the nonlocality of quantum wavefunctions, and the notion that creative genius (similar in character to genius as conceived in the humanities -- a perceiving of hidden relationships between remote areas of experience) is required to develop an insight that leads to new understanding. The students will realize that humanists also explore the world by asking "What if?" and develop consequences in response to this question, that poetry is also about categorizing our existence, and that elegance, economy and beauty are apparent in all forms of knowledge.

Beyond this, it is hoped that students will leave the course with a deeper insight into what the University is about, that connections will be made across quite disparate fields, and the undertakings of both scientists and humanists will not appear so very different in some respects, even if the topics they are studying are quite different.

III. ASSESSMENT

The effectiveness of the inquiry-based and problem-solving format of our courses was evaluated throughout each semester and at the conclusion of each term. Additional assessment

was conducted at subsequent times, allowing students and faculty to reflect upon their experiences from a later perspective.

During the implementation of these courses, the conceptual development of students was assessed continuously by virtue of the interactive and hands-on nature of these course activities.

At the end of each semester, the Student Course Opinion Questionnaire was administered. This instrument, available to all instructors in the College, asks students to give their opinions about their own active participation and about the effectiveness of the course and the instructor. This instrument revealed the students' general endorsement of these courses, as in the following rankings:

Life's Devices **Overall course rating (5 pt scale, 5 = highest rating)**

	<u>1997</u>	<u>1998</u>	<u>1999</u>
mean	4.11	4.57	4.33

Overall instructor rating (5 pt scale, 5 = highest rating)

	<u>1997</u>	<u>1998</u>	<u>1999</u>
mean	4.78	4.86	4.89

Physics by Inquiry **Overall course rating (5 pt scale, 5 = highest rating)**

	<u>1998</u>	<u>1999</u>	<u>2000</u>
mean	4.17	4.25	3.22

Overall instructor rating (5 pt scale, 5 = highest rating)

	<u>1998</u>	<u>1999</u>	<u>2000</u>
mean	4.50	4.58	4.11

Clockwork to Chaos **Overall course rating (5 pt scale, 5 = highest rating)**

	<u>1996</u>	<u>1998</u>	<u>2000</u>
mean	4.55	4.21	4.27

Overall instructor rating (5 pt scale, 5 = highest rating)

	<u>1996</u>	<u>1998</u>	<u>2000</u>
mean	4.73	4.71	4.27

To augment these numerical rankings, more extensive information about students' experiences was solicited by several methods. For example, students in Frank Wolfs' *Physics by Inquiry* course wrote essays at the conclusion of the semester about their participation in this course. Students noted general enthusiasm for this hands-on method of physics learning and

made observations about very specific experiences. Since this course began with instruction in how to calibrate instruments, several students outlined their acquisition of the scientific thinking that necessitates such a thoughtful, methodical approach to understanding measurement. Some students described their initial confusion about the equipment and the experiments and asked for more help with these technical concerns:

I would also suggest that the first few class periods of the class be solely devoted to getting to know the computers and how the software works. Many times I understood concepts yet the computer problems got in the way.

Another student noted:

The lab was a new environment, very different from my lab experiences in high school and I repeatedly asked myself, what are these people asking me to do? I had never seen a motion sensor before and the fact that it needed to be calibrated before I used it was a completely new concept to me.

Later they came to understand the goals and the process of experimentation:

The class started with the most fundamental of experimental processes by calibrating the systems used to measure the experiments we would be conducting. This taught the student when, how, and where to rely on the equipment so essential to obtaining experimental data. At first, this did not appear to help my physics knowledge, but by the end of the course a student becomes so dependent upon the systems that help him or her understand physics that the equipment actually represents the student's first line of analytical ability.

Another student described how this careful thinking about instrumentation early in the course continued to help her learn later throughout the semester:

I remember we started the semester off with measuring the bounds of the motion detector. We decided that it could not produce an accurate reading at less than .4 m and that the further away we got from the sensor, the more likely we were to have it bounce off of other objects and produce incorrect measurements. The day or two that we spent on that calibration exercise stuck with us the entire semester. When we were in the very last week or two, we had to use the motion sensor to find a line of best fit, from which the slope equals velocity. A concept I learned along the way. Later in this lab, the motion sensor was on the floor, and a mass was hanging from a spring off the lab top. After [another student's] and my first run, we had a beautiful oscillation graph, but at the bottom, the motion went unregistered. After pondering it a minute or two, we both remembered the .4 m rule. Again, we were able to take information learned at the very beginning of the semester, and apply it to much more involved experiments.

Other students expressed their appreciation for the access to this level of experimentation:

Physics 105 exposed me to many pieces of equipment such as: Science Workshop Interface, a 1.22 meter track, a dynamics cart, Smart Pulley, PASCO motion sensor, force sensor, magnetic bumpers, just to name a few. More importantly, this class gives non-science students the opportunity to experience science research. We, students never slept through a class because we were constantly doing another experiment, which allowed us to physically see the principles and laws in action.

They learned how to regard data. One student noted:

My most priceless instruction followed a very unscientific behavior of disregarding data that did not fit my predictions, or theory. Disregarding data obtained through a valid experimental process is unacceptable. Certainly, very serious conditions must be met before one can engage in this type of activity.

Another *Physics by Inquiry* student made a similar comment about data analysis:

This brings me to the one thing that I never could have learned in any other class quite so well. NEVER MESS WITH YOUR DATA!!!! I think if there is one thing we all learned, it is that you can't throw away your data just because it does not fit other pieces of data. Further, we learned ways in which we can reason through our weird calculations and results.

Students in the *Clockwork to Chaos* course were asked to add written comments to the Student Course Opinion Questionnaire. A common concern related to the extensive scope of the material within very limited time. In response to the question, “What are the major weaknesses of the course,” a number of students responded with comments like the following:

Lack of time. The designated period goes by very fast, perhaps expanding it to 2 semesters would be wise.

So much material, so little time. We weren't able to cover a large portion of the subjects on the syllabus.

I'd have liked to go more in depth on certain books and not move so quickly past so many—especially the shorter poems and stories.

When asked about the strengths of the course, *Clockwork to Chaos* students strongly endorsed the opportunity to combine the two perspectives of science and the humanities:

The combination of one literature-oriented mind and one science-oriented mind was enriching for our class discussions. I found myself stimulated from each and every lecture. I would take this course again in a second.

It [the course] truly does give the students a chance to think. Instead of just learning about literature and science as separate entities, we get to

integrate them. It's amazing how much one lives within the other, and how each changes and processes through the development of the other as well.

Faculty reflected upon their experiences in these courses as well. John Lambropoulos and Renato Perucchio emphasized that the *Life's Design* has been intended to serve as an opportunity for non-science students to learn about the process of design:

Design is a fundamental part of all engineering curricula, and is currently often taught as a capstone course after the students have completed the entire math, physics, and engineering analysis courses. Our goal in teaching our Quest course is to educate non-engineering students at UR about the process of design. What are design constraints, how these constraints are implemented, the issues which arise when designing a product, how these issues are resolved, and how creativity is perhaps more important than technical expertise in successful design of products.

Design is an open-ended, creative process in which there is no unique, correct solution to a design problem. Rather, there may be many "correct" solutions, all of which may meet the design constraints. Part of our course goals is to show to non-science majors taking our course that, contrary to the often held belief that in science there is always a correct solution, the design process is open-ended and may admit of many correct solutions.

During the Spring Semester 2000, Dean of Freshmen, Dale McAdam, collected faculty and student opinions for a report on Quest and Quest-like courses, which included the courses developed as part of this project. Quest courses, are designed principally for first-year and some second-year students, are small, problem-centered courses that employ a research-based pedagogy and introduce students to the distinctive nature of college learning. The goals of Quest courses are very similar to the goals we developed for our courses, except that most Quest courses try to attract students majoring in the course discipline, while our development focusing on the non-majors. Nevertheless, the report provided valuable feedback about the success of the research/inquiry-based pedagogy. The faculty reflected on the concentration and skill required to guide students in these high-intensity courses:

Quest teaching is full contact teaching. I must admit that the idea of waiting in silence for a student to summon the courage to take a stab at an answer, and then having to think quickly to make use of that answer and connect it to broader themes of the course is a new tactic for me, and a powerful one. (Ian Walmsley)

Socrates was right: Learning of the most intense kind takes place through dialogue. (Daniel Albright)

Dean McAdam found that students emphasized their appreciation for real interaction with faculty:

We were allowed to talk “out of bounds” as opposed to recycling information recited to us in a lecture hall.

Quest courses allow students and faculty to develop good working relationships earlier in the college experience, making them more beneficial for both parties.

McAdam notes that students choose these courses because “they match their interests, not because they meet college requirements.”

Another opportunity to evaluate the effectiveness of this course format was afforded by Lynn Donahue, who recently completed her dissertation for the University of Rochester’s Margaret Warner Graduate School of Education and Human Development. The subject of her dissertation, entitled “*Students’ Perceptions as Experiential Learners in Courses Defined as Experiential*,” included an art class and Frank Wolf’s *Physics by Inquiry* course. She found that students perceived their learning in these courses as “engaging, reflective, and self-reliant, and relevant.” She particularly noted the importance of what she termed “catalytic events” that propelled students toward more active learning and the need for students to connect classroom learning with their own personal systems of meaning making.

IV. GENERAL IMPACT OF PROJECT

The courses that were developed as part of this project are highly successful. A total of 161 students have taken these courses since they were first offered. Details about the student enrollment in our courses are provided in Table 1.

All students enrolled in *Physics by Inquiry* are non-science majors while the students enrolled in *Life’s Devices* and *Clockwork to Chaos* come from the science and non-science divisions. Most non-science students enrolled in our courses take our courses to satisfy their Cluster requirements. Details on the number of students enrolled in clusters of which our courses are part are listed in Table 2.

The enrollment in our courses is limited to 20 – 40 students in order to ensure optimum interaction between faculty and students, and to ensure the creation of a small group environment. In addition, resource limitations also required us to limit the enrollment.

Although the courses we developed have a significant impact on the education of our non-science majors, the overall project has had a much broader impact on the undergraduate education for both our science and our non-science majors. Some specific examples of the impact are:

- The cross-disciplinary effort that created the foundation for this project has fostered many other cross-disciplinary initiatives between Departments in all divisions of the College. These initiatives resulted in the development of many cross-disciplinary clusters. Examples of such clusters are *Science of Light and Sound* which includes courses from the Department of Physics and Astronomy, the Institute of Optics, and Department of Brain and Cognitive Science, *Origins* which includes courses from the Department of Physics and Astronomy, the Biology Department, and the Department of Earth and Environmental Science, and *Modern Technology* which includes courses from the

Course	Semester	Number of Students
<i>Life's Devices</i>	Fall 1997	13
	Fall 1998	7
	Fall 1999	10
	Fall 2000	31
<i>Physics by Inquiry</i>	Spring 1998	12
	Spring 1999	13
	Spring 2000	13
	Spring 2001	19
<i>Clockwork to Chaos</i>	Fall 1996	13
	Spring 1998	15
	Spring 2000	15

Table 1. Student enrollment in the courses developed as part of this project.

Department of Mathematics, the Institute of Optics, the Departments of Electrical and Mechanical Engineering, and the Chemistry Department.

- The success of the courses developed as part of this project, have resulted in the development of inquiry-based courses in other Departments. Good examples of such courses are “Music and Electrical Engineering” which resulted from a collaboration between the Eastman School of Music and the Department of Electrical Engineering and “Building the city in the in the ancient world: Engineering and architectural achievements in Roman and Medieval” which is the result of a collaborative effort between the Department of Mechanical Engineering and the Department of Art and Art History.
- Our success with the inquiry-based approach has resulted in the development of other inquiry-based courses in our own disciplines. For example, the *Physics by Inquiry* course

Cluster	Number of Students
An Introduction to the Physical World	16
Quantitative Physics	16
Science -- Discovery, History and Methodology	42
The Nature of the Universe	66
Introduction to Physical Science	15
Science and Technology by Inquiry	1
The Scientific Method	2
Biomechanics	0
Biomedical Engineering	0
Design with Materials	0
Engineering Design	0
Literature, Science and Technology	0

Table 2. Details about cluster enrollment in clusters of which *Life's Devices*, *Physics by Inquiry*, and *Clockwork to Chaos* are part.

served as a model for the development of the *Astronomy by Inquiry* course that was offered for the first time in Fall 2000.

- Our success with the inquiry-based approach has resulted in changes in already existing courses. For example, the workshop approach used in several introductory courses in Chemistry, Biology, and Physics was changed to feature a more inquiry-based approach.
- Our development was made possible by the support from the College Dean's Office, which provided the required matching funds. The success of this project has resulted in the commitment of the Dean's office to ensure the availability of ongoing funds for this type of developments.
- The classroom that was constructed for the *Physics by Inquiry* course is heavily being used by other courses, some of which were created specifically with this resource in mind. Examples include various Graphics Art courses, English courses, and various Physics and Astronomy courses.
- The efforts to develop new approaches to teaching science have been recognized by the University of Rochester. Two co-PIs of this project have received Goergen awards for Distinguished Achievement and Artistry in Undergraduate Teaching at the University of Rochester. In 1997, the *Life's Devices* course was awarded the Sykes innovative curricular award for engineering students, and in 1999 this course was nominated for a curriculum innovation award by the American Society of Mechanical Engineers (ASME).

The faculty involved in this project have come to realize that with new approaches to learning, new tools must be developed to evaluate the impact of the changes we make on the learning process of the students. The change in thought process about goals and assessment has forced us to better define our course goals, not only for the courses developed as part of this project, but also for the other courses we teach. The change in our thought process was also shared with other faculty during a workshop organized in the 1999 – 2000 academic year that focused on assessment.

V. CONCLUSIONS

The funds provided by the National Science Foundation have provided us with the tools to start reform of our undergraduate education. The success of our initiative, will have a long lasting effect on how we think about teaching. The tools and techniques developed as part of this program, and the stories of its success, will provide the incentive to others in the College to implement our approach to learning in many other courses, both for science and for non-science majors. Although the number of students enrolled in each course will never be large, the increase in the number of courses that use the inquiry-based approach will ensure that a large fraction of the students studying at the University of Rochester will encounter several inquiry-based courses during their stay in Rochester.