# Physics

## CRAFTY Curriculum Foundations Project
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Karen Cummings and Guy Emery, Report Editors
Guy Emery and William Barker, Workshop Organizers

## Summary

For success in introductory physics, the workshop participants believe that it is most important for students to be able to think operationally within the context of a few fundamental mathematical concepts. While formal theoretical knowledge of the concepts and a tool bag of techniques and computational skills are desirable, the most important factor is that students gain enough active understanding that they are able to think through and solve a wide variety of problems involving the fundamental concepts in a wide variety of contexts. In particular, we present several statements about the general nature of mathematics instruction relevant to the needs of physics students:

1. Conceptual understanding of basic mathematical principles is very important for success in introductory physics. It is more important than esoteric computational skill. However, *basic* computational skill is crucial.
2. Development of problem solving skills is a critical aspect of a mathematics education.
3. Mathematics instruction is worthwhile not only in developing problem-solving skills but also in exposing students to "how a mathematician sees the world." On this point Anthony French of the Massachusetts Institute of Technology says,

    *This is a point of view, a rigor, that we value but wouldn't attempt and can't afford in the introductory physics classroom.*

4. Introductory mathematics courses should be taught by the best, most skilled teachers; in most cases, that means professors or advanced graduate students.
5. Courses should cover fewer topics and place increased emphasis on increasing the confidence and competence that students have with the most fundamental topics.
6. There are several mathematical topics that are very important for students who will take introductory physics. We list these topics in a table in the next section of this report.
7. Technology should not have a major effect on what mathematics is learned in the first two years. Computers are most helpful for visualization, and for handling problems that are otherwise impracticable. Most instructors of introductory physics are not using symbolic manipulation packages. Spending time in mathematics courses teaching students to use such programs does not directly help in introductory physics courses. However, knowledge of such software is helpful once students enter upper-level physics courses.
8. It is very important to have dialog between the disciplines about what is needed in introductory courses.
9. The impact of mathematics teaching reform on the performance of students in physics courses has not yet made itself felt. However, there is great potential synergism between mathematics education reform

and physics education reform. Ernst Breitenberger made a strong encapsulating statement, which with minor editing may be given as:

*The learning of physics depends less directly than one might think on previous learning in mathematics. We just want students who can think. The ability to actively think is the most important thing students need to get from mathematics education.*

# Narrative

## Understanding and Content

**What conceptual mathematical principles must students master in the first two years? What broad mathematical topics must students master in the first two years? What priorities exist between these topics?**

There were several conceptual mathematical principles that the panel suggested should be mastered in the first two years of mathematics instruction. For example, students should understand that mathematics is the language of science and engineering, and that they must be able to use the language to communicate their knowledge of these other disciplines. They need to be able to translate a problem written in words into the corresponding mathematical statement. Then they must have the computational skill to solve the problem. They must develop a belief in mathematical rules and a comfort with symbols, diagrams, and graphs. They must learn to distinguish between a mathematical concept and techniques for calculation of solutions. (For example, students should know that being able to integrate is quite different from understanding what integration is). They must go beyond "learning rules" to develop understanding. They must acquire "operational" knowledge.

In terms of topical coverage, the panel felt that a solid, deep, functional understanding of the basics was so important that, to make it possible to achieve it, they were ready to reduce exposure to the complexities and intricacies of more difficult ideas and techniques. For example, effective introductory physics instruction requires that students have complete confidence in their ability to understand and calculate simple derivatives and integrals. The more esoteric and complicated topics are not of use in the introductory courses. Furthermore, they are forgotten (and must be re-learned) by the time students reach upper-level courses.

To be successful in undergraduate physics courses, students must understand the *concepts* of function, derivative (as a rate of change and a slope), and integral (as a sum, an area, and an antiderivative). They must also have well-placed confidence in their trigonometric and algebraic skills.

There was significant agreement regarding the topics needed by students taking introductory physics courses. There was also significant agreement about the priorities among these topics. This is summarized in the following table.

| **Priority** | **Topics** |
|---|---|
| Highest | Behavior of Simple Functions |
| | Derivatives of Simple Functions |
| | Integrals of Simple Functions |
| Higher | Limiting Cases |
| | Differential Equations |
| | Maximum/Minimum Problems |
| | Line and Surface Integrals |
| | Vector Operations |
| High | Series and Sequences |
| | Polar and Other Coordinate Systems |

By "simple functions" we mean those on a par with polynomials, sine, cosine, tangent, natural logarithm, and exponential functions. "Limiting cases" refer to questions such as "What is the behavior of *e-kt* as *t* gets very large or very small and *k* is either positive or negative?"

**What mathematical problem solving skills must students master in the first two years?**

The panel judged the development of problem-solving skills to be very important. This was initially expressed as the importance of "teaching students to think." Several panel members thought this was *the* most important outcome of a good mathematics education. The panel was unanimous in suggesting that practice in solving problems should be extensively couched in real-world contexts that are meaningful to the students. Ernst Breitenberger said:

> *I investigated a situation in which physics graduate students were found to be more successful as mathematics teachers than a cohort of mathematics graduate students. The indication was that this was because the physics graduate students used real life examples to teach the mathematics rather than teaching the mathematics without context.*

Several related skills were identified as being important in the development of problem solving abilities. Namely, students should be able to focus a situation into a problem, translate the problem into a mathematical representation, plan a solution, and then execute the plan. Finally, students should be trained to check a solution for reasonableness. Peter Heller, of Brandeis University, adds:

> *Students should get exposure to the general (marvelous) idea that approximations lead to exactitudes.*

**What is the desired balance between theoretical understanding and computational skill? How is this balance achieved?**

Students need conceptual understanding first, and some comfort in using basic skills; then a deeper approach and more sophisticated skills become meaningful. Computational skill without theoretical understanding is shallow. However, computational skill in several different contexts is usually necessary in development of a more complete understanding of a concept. In discussing theoretical understanding, the panel argues that students should understand the ideas rather than formal proofs. Students should be able to calculate simple cases with great facility. More complicated cases can be left to technology. To achieve the required level of computational skill, most students need significant practice, so some drill-type problems may be required.

## Technology

**How does technology affect what mathematics should be learned in the first two years?**

The ubiquity of information technology has increased the importance of, and need for, training in computer science. The resulting rise in the number of students taking computer science courses indicates a need for a discrete mathematics curriculum that parallels the existing calculus-based curriculum.

Except for that aspect, technology should not fundamentally affect what students learn in their first two years of mathematics instruction. The increased importance of technology to society may have an effect on the topics instructors choose to cover in introductory physics courses. Regardless, the requirements for mathematical preparation of students will not shift significantly, even if additional contemporary technology-related topics are incorporated into introductory physics courses.

Furthermore, the increased prevalence of instructional technologies, e.g., graphing calculators and computers in the classroom, should not fundamentally affect what mathematics students learn in the first two years. Computers offer extraordinary possibilities for enhanced mathematical learning through visualization. Additionally, they relieve the burden of mundane but intricate calculations, and thereby allow instructors to address real world problems that previously were "too messy" to be discussed. However, technology should not drive the curriculum in any way.

The use of computers and symbolic manipulation software in introductory mathematics courses does make possible a desirable shift in emphasis among secondary skills and topics. For example, the memorization of esoteric integration techniques could be displaced by development of skill in prediction of approximate answers and evaluation of whether an answer produced by the computer or calculator is reasonable. Such a shift in emphasis would reinforce changes widely supported by physics education researchers.

Larry Kirkpatrick of Montana State University, former President of the American Association of Physics Teachers, effectively sums up the dominant opinion. He writes:

> *…[T]echnology (in the mathematics curriculum) allows students to spend their time understanding the basic, simple cases, both conceptually and algorithmically. Once students have mastered the simple cases, they can use technology to obtain results for the more complicated cases, much as practitioners or researchers do. When used in this way, technology also better prepares them for entering the work force.*

### What mathematical technology skills should students master in the first two years?

There is general agreement among the panelists that some experience with a symbolic manipulation program like *Mathematica* or *Maple* is desirable. However, the point was clearly made by several individuals that these skills are typically not exploited in introductory physics courses. Use of *Maple* or *Mathematica* in an introductory physics course diverts too much of the students' time and attention away from learning the fundamental physics. Hence, development of that kind of skill is only of significant value once students enter junior and senior level physics courses. At that point, such skill is easily exploited to facilitate further learning.

Specifically, students should become skilled in basic computational techniques. For example, they should become very comfortable with the use of symbols and naming of quantities and variables. They get important experience with this when they work on realistic (real world) problems. They should be fluent in the use and meaning of the derivative, and should be able to formulate and solve simple differential equations. They should also be able to use a calculator or computer to solve simultaneous algebraic equations. Peter Heller gave a compelling alternative opinion:

> *Spread sheets are by far the best medium (for teaching with technology) since data, text and graphics are all visible at once, and since the techniques are easily learned and useful for numerical approximations.*

## Instructional Techniques

### What instructional methods best develop the mathematical comprehension needed for your discipline?

While the panel did not have enough specific knowledge of the methods typically used in mathematics instruction to answer this question very fully, there were a number of general responses. The methods chosen for use should be based on research about the ways students learn and the ways they don't. In general, any method that teaches conceptual understanding as well as useful algorithms was acceptable. There was no objection to drill practice as a way to develop competency in using simple algorithms.

Peter Heller points out that his research, which is based on interviews with hundreds of students, indicates that the traditionally used methods of mathematical instruction fail to reach the vast majority of students. In a paper to be published he writes:

> *When it comes to conceptual understanding of the basics, the traditional methods of calculus instruction did not seem to have reached most of the students I interviewed. Let me give an example. All the students could say that the derivative of the function $y = f(x) = x^2$ is $f'(x) = 2x$. But when asked: "Can you use that to estimate the square of 10.1 knowing that 102 = 100",*

*the vast majority didn't know where to begin, said that y was 2Δx, or that Δy was 2Δx (thereby relating a finite quantity with a small-increment). When I did this sort of thing five years ago for the natural logarithm function I even saw Δx going into the denominator! All in all, they didn't seem to appreciate that calculus is fundamentally about numbers.*

**What guidance does educational research provide concerning mathematical training in your discipline?**

*A great deal. However, education research results must always be adapted to the local constraints. This is typically a subtle process. Engineering is a good model for how to apply a general principle to a local situation even with imperfect knowledge.*

— Kenneth Heller, Professor of Physics, University of Minnesota and former Chair of the American Physical Society's Forum on Education.

Education research indicates basic methods that generally lead to increased pedagogical efficacy regardless of discipline. Such research indicates, for example, that students must have hands-on experience with the material, that examples should be "real world," that there should be a focus on understanding the fundamental concepts in several different representations (natural language, graphical, symbolic, . . .), and that fewer topics should be covered and those topics included should be covered in greater depth.

## Instructional Interconnections

**What impact does mathematics education reform have on instruction in your discipline?**

To date, the impact of mathematics education reform on physics instruction has been small. However, the panel feels that the potential impact is great. We hope mathematics education reform will reinforce similar efforts in physics education reform, since these movements stem from a common philosophical viewpoint and hence advocate similar approaches to instruction.

If the result of mathematics education reform is that students have a deeper understanding of fundamental mathematical concepts and a heightened ability to do basic mathematical manipulations, the impact on physics instruction will be large and positive. Improvements in conceptual understanding of mathematical ideas will greatly facilitate conceptual learning in physics. Improved learning (understanding) of simple algorithms by spending more time on them and less time on more esoteric algorithms would be very useful. However, it is also clear that unless the reform is done carefully, the removal of important topics could have a significant detrimental effect on physics instruction.

Perhaps Stanley Haan, Professor and Chair, Department of Physics and Astronomy at Calvin College, made the most thoughtful comment related to the potential impact of mathematics education reform. He said:

*(Mathematics education reform) will have an enormous impact on physics if it can help to change students' conception of what 'good teaching' ought to be like.*

**How should education reform in your discipline affect mathematics instruction?**

On this topic, Barry Holstein, Professor of Physics, University of Massachusetts, wrote:

*The essence of education reform in physics is in creating methods of instruction which are more effective in conveying knowledge that students retain. Such methods are universal and certainly have relevance to instruction in mathematics (and other subjects).*

The panel agreed. The basic ideas about "best practice" in instruction are not likely to be highly discipline specific. For example, Peter Heller suggests that statements made within the physics education community (like "start from where the student is, not where the teacher thinks the student is," and "really try to understand what is in the mind of the student") are directly applicable to mathematics education as well. In addition, Kenneth Heller argues that physics education reformers' suggestions that students should get extensive practice with writing reasons for their answers, with communicating their thoughts on procedures, with solving real problems (where the path to the answer is not known by the student at the beginning), with applying their knowledge in a context meaningful to them, with making connection to other domains of their knowledge, and with working effectively in cooperating groups, are directly applicable to mathematics instruction.

Consistency of approach in mathematics and physics, and mutual reinforcement, may be quite important in helping each student achieve his or her own potential. Furthermore, physics and mathematics education reforms should be coordinated so they can be supported by both disciplines, and so that both disciplines can benefit from research findings.

# WORKSHOP PARTICIPANTS

(See the Appendix for detailed biographies.)

**Ernst Breitenberger**, Professor of Physics, Emeritus, Ohio University
**Karen Cummings**, Assistant Professor of Physics, Rensselaer Polytechnic Institute
**Guy Emery**, Professor of Physics, Emeritus, Bowdoin College
**Anthony French**, Professor of Physics, Emeritus, Massachusetts Institute of Technology
**Stanley Haan**, Professor and Chair of Physics and Astronomy, Calvin College
**Randal Harrington**, Physics Teacher, San Jose High School
**Kenneth Heller.** Professor of Physics, University of Minnesota
**Peter Heller**, Professor of Physics, Brandeis University
**Barry Holstein**, Professor of Physics, University of Massachusetts, Amherst
**Larry Kirkpatrick**, Professor of Physics, Montana State University
**Malgorzata Zielinska-Pfabe**, Professor of Physics, Smith College

### Mathematics Participants

**Thomas Banchoff**, Professor of Mathematics, Brown University
**William Barker**, Professor of Mathematics, Bowdoin College
**Thomas Berger**, Professor of Mathematics, Colby College
**Susan Ganter**, Associate Professor of Mathematical Sciences, Clemson University
**Deborah Hughes Hallett**, Professor of Mathematics, University of Arizona
**Harvey Keynes**, Professor of Mathematics, University of Minnesota
**William McCallum**, Professor of Mathematics, University of Arizona
**Donald Small**, Professor of Mathematics, U.S. Military Academy, West Point

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# APPENDIX: Biographies of the Workshop Participants

**Ernst Breitenberger** earned a Dr. phil. in real functions under Johann Radon in Vienna, 1950. Thereafter, he earned his keep on four continents mostly in physics and its penumbra. He has worked in the areas of high-voltage engineering; low-energy nuclear experiments (Ph.D. Cambridge, 1956); theoretical physics; statistics and stochastic processes; operations research; science history and biography. He was Professor of Physics at Ohio University in Athens, Ohio, from 1963; becoming emeritus in 1994. His concern about the teaching of mathematics to non-mathematicians led to a semi-quantitative study and an article entitled: "The Mathematical Knowledge of Physics Graduates," American Journal of Physics 60, 318–323 (April 1992).

**Karen Cummings** received her Ph.D. from the University at Albany, State University of New York, in 1996. Her dissertation research involved the use of nuclear reaction analysis and scattering techniques for materials analysis. Dr. Cummings joined the faculty at Rensselaer Polytechnic Institute in 1997 following a one year sabbatical replacement position at Skidmore College. She is currently the Edward Hamilton Clinical Assistant Professor of Physics at Rensselaer. Professor Cummings was awarded the Hamilton title in recognition of her innovative work in undergraduate physics education. In addition to her teaching, she does federally funded research on the learning and teaching of introductory university physics. Her current funded projects include the development of a tool for assessment of student problem-solving ability, curriculum development for introductory courses and using assessment as a guide to increased learning outcomes in first year physics courses. Professor Cummings is the course supervisor for the Studio Physics I course at RPI, which involves eight faculty members, ten teaching assistants and 600 students per semester in an active engagement style course. She is currently working on a revision of the widely used physics textbook, *Fundamentals of Physics.* The revised text will incorporate modern pedagogical approaches and research in physics education. It will be titled *Fundamentals of Physics* by Halliday, Resnick, Walker and Cummings and is scheduled for release in the Fall of 2001.

**Guy Emery** studied at Bowdoin (A.B. 1953) and Harvard (Ph.D. 1959). He was at Brookhaven National Laboratory (1959–1966), then moved to Indiana University where he became Professor of Physics. He worked at the Indiana University Cyclotron Facility, where he was Liaison Officer for the Users Group (1970–1979) and Associate Director for Research (1972–1979). Professor Emery returned to Bowdoin in 1988 as Department Chair and became emeritus in 1998. He has also been a visitor at the State University of New York at Stony Brook, Groningen, and Osaka. His research papers are in the areas of nuclear spectroscopy and nuclear structure, chemical and solid-state effects on nuclear processes, nuclear reactions with large momentum transfer, and production of pions near threshold. In recent years he has been actively pursuing the history of twentieth-century physics.

**Anthony French** is Professor of Physics, Emeritus, at Massachusetts Institute of Technology. He received his B.A. (1942) and Ph.D. (1948) at Cambridge University, and was demonstrator and Lecturer (1948–1955) at the Cavendish Laboratory where he did research in nuclear physics. He was Professor of Physics at the University of South Carolina (1955–1962, Dept. Head 1956–1962) and Visiting Professor at MIT (1962–1964) while working on a physics curriculum development project for undergraduate students. He was Full Professor at MIT from 1964–1991. Dr. French has authored textbooks, student experiments, demonstrations, and films. His textbooks include: *Special Relativity, Newtonian Mechanics, Vibrations & Waves, Introduction to Quantum Physics* (with E. F. Taylor). He is editor of *Einstein: A Centenary Volume* (1979) and co-editor of *Niels Bohr: A Centenary Volume* (1985). Professor French was awarded the Institute of Physics (UK) Bragg Medal in 1988, the American Association of Physics Teachers' Oersted Medal in 1989 and the Melba Phillips Award 1993. He was President of the AAPT from 1985 to 1986. His chief current professional interests are the subject matter of undergraduate physics and the history of physics.

**Stanley Haan** is Professor and Chair in the Department of Physics and Astronomy at Calvin College in Grand Rapids, Michigan. He received his Ph.D. in 1983 from Colorado. His professional interests are in theoretical atomic physics, especially as relating to photorecombination and strong-field photoionization, and in science education, especially as relating to elementary school science. Professor Haan has thirty-two physics research publications, including eight with 13 different undergraduate research assistants as co-authors. He has been principal investigator on several National Science Foundation grants for physics research and is co-principal investigator on a NSF grant to develop a course in scientific analysis for elementary-education students. He is actively involved in course development for elementary education students and has three science-education publications. Professor Haan has led numerous workshops for elementary school teachers.

**Randal Harrington** is the founder and former Director of the Laboratory for Research in Physics Education at the University of Maine, is currently teaching High School Physics in San Jose, California. He received his Ph.D. in Physics from the University of Washington in 1995 and has over 20 years of teaching experience. Dr. Harrington is active in the American Association of Physics Teachers where he has served as the Chair of the Committee on Research in Physics Education. In the past, he has received funding from the National Science Foundation, served on national physics test construction committees, and has organized and run numerous workshops and seminars on teaching physics and integrating technology into the science classroom. He has also served as a content consultant for both Microsoft and the education division of WGBH, and has worked as either a consultant or an external evaluator on numerous physics reform projects. In 1997, Dr. Harrington was awarded a Higher Education SEED's Fellowship from the Maine Mathematics and Science Alliance and the Maine Department of Education for his work with preservice teachers and for reforming the introductory physics course at the University of Maine. Dr. Harrington has co-authored several curricula including units on electric charge, magnetism, radiation and radioactivity.

**Kenneth Heller** received his B.A. from the University of California (1965) and his Ph.D. in physics from the University of Washington in Seattle in 1973. He became research associate and instructor at the University of Michigan in 1972 and joined the faculty of the University of Minnesota in 1978, becoming Professor of Physics in 1986. Professor Heller was visiting professor at the University of Utah in 1985 and a member of the board of trustees of the Universities Research Association (1985–1988). He has been principal investigator in high energy physics at Minnesota since 1989. His experimental particle physics research has included studies of quark dynamics from strong interactions of hadrons, quark confinement from magnetic moments of baryons and their weak decay properties, and muons from high energy interactions. Professor Heller was Chair of the American Physical Society's Forum on Education at the time of the Worskhop.

**Peter Heller** was educated at MIT and received his Ph.D. from Harvard University in 1963. Following postdoctoral research at MIT, he joined the faculty at Brandeis (Asst. Prof. 1966, Prof. 1974). His experimental researches on phase transitions and critical phenomena helped launch the modern era in that subject. He also has a long-standing interest in mathematics and physics education going back to 1958, when he worked in an NSF-sponsored program for the training of high school teachers of science and mathematics. Since 1982 he has devoted all his time to developing novel physics and mathematics teaching experiments and approaches at levels ranging from high school to graduate school. This has led to several well-known papers and participation with several groups including the editorial board of the American Journal of Physics. At Brandeis, Professor Heller has been a recipient of the university-wide Louis Dembitz Brandeis Prize for Excellence in Teaching. Within the past year he has been cited by graduating seniors as one of the "most influential teachers" with respect to contributions to student intellectual development. Analysis of student comments shows this to be largely due to his efforts in the teaching of mathematics within physics courses. This aspect has involved more than a thousand hours of interviews and Socratic teaching sessions with individual students.

**Barry Holstein** was educated at Carnegie Tech (B.S. 1965, M.S. 1967) and Carnegie-Mellon University (Ph.D. in physics, 1969). He became instructor in physics at Princeton in 1969, joined the faculty at the University of Massachusetts in 1971, and became full professor in 1979. He has been visitor at Princeton (fellow 1975–76, Prof. 1985) and program officer in theoretical physics at the National Science Foundation (1977–1979). He is a theoretical physicist who has specialized in weak interactions, including nonleptonic weak processes, weak decays of nuclei, and chiral symmetry. He has published several pedagogical articles in the American Journal of Physics, most recently "The Neutrino," with Wick Haxton, 68, 14–31 (January 2000).

**Larry Kirkpatrick** is Professor of Physics at Montana State University. He received his Ph.D. in experimental high energy physics from MIT in 1968. After five years at the University of Washington, he moved to Montana State University as a teaching specialist in physics with the responsibility for training teachers and improving the teaching of physics at all levels. In addition to his extensive activities in state and national physics and science teaching organizations, Professor Kirkpatrick served for eight years as a coach of the US Physics Team. He also co-writes the physics contest column and serves as the field editor for physics for *Quantum Magazine*, a joint US-USSR publication for bright students in mathematics and physics. Professor Kirkpatrick has been recognized for his physics teaching (Phi Kappa Phi Outstanding Teaching Award and the Burlington Northern Foundation Faculty Achievement Award for Outstanding Teaching) and his service to the physics teaching profession (Distinguished Service Citation from the American Association of Physics Teachers and a Merit Citation from the Montana Science Teachers Association). He was President of the American Association of Physics Teachers at the time of the Workshop, and is a fellow of the American Physical Society and a member of the Governing Board of the American Institute of Physics. In addition to his 14 research publications in high energy physics, he has published a textbook (*Physics: A World View*) now in its third edition, seven articles on physics education, and numerous reviews and news articles. In his service to the physics teaching profession and the general public, Professor Kirkpatrick has given more than 300 workshops and presentations.

**Malgorzata Zielinska-Pfabe** received her M.Sc. degree in theoretical physics from the University of Warsaw, Poland. She received her Ph.D. in nuclear physics (1969) from the Institute of Nuclear Research in Warsaw, where she worked as a research fellow until 1978. She was a visiting researcher at Rensselaer Polytechnic Institute from 1978 to 1982. In 1982 she joined the faculty at Smith College, and became a full professor in 1984. Professor Zielinska-Pfabe was awarded the first Smith College Senior Faculty Teaching Award in 1985 and is a fellow of the American Physical Society. In 1992 she was appointed to the Sophia Smith Chair in Physics. Professor Zielinska-Pfabe's field of research is theoretical heavy ion physics. She has published over 50 papers in refereed professional journal in the US, Europe, and Australia, and authored over 50 professional abstracts and conference proceedings.