MATTER & INTERACTIONS

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Abstract:

Matter & Interactions is a modern calculus-based introductory curriculum that emphasizes the power of fundamental principles, and guides students through the process of starting from these principles in analyzing physical systems, on both the macroscopic and the microscopic level. The continual emphasis on the application of fundamental principles and on the atomic nature of matter makes possible the integration of topics that are traditionally taught as disconnected: mechanics and thermal physics are intertwined, and electrostatics and circuits are analyzed using the same tools for both topics. The development of the curriculum has been shaped by research on learning and on research in physics education. For additional information, see http://www4.ncsu.edu/~rwchabay/mi.

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1. Introduction and outline

Matter & Interactions (M&I) is a new curriculum for the introductory calculus-based physics course taken by engineering and science students. Because it represents a change in the content and emphases of the course, it differs in nature from many of the other reforms discussed in this volume, which focus on pedagogical innovations, some specific to the traditional introductory physics curriculum, others involving changes to the learning environment which are not specific to a particular sequence and content.

Section 2 of this paper describes the need for change in the content, sequence, and emphases of the introductory course. The particular goals of the *Matter & Interactions* curriculum are elucidated, and there is a brief overview of the organization of the curriculum.

Sections 3 and 4 discuss in some detail the selection and sequence of topics in the curriculum. Section 3 discusses the topics in Volume I, *Modern Mechanics*, which corresponds to a typical first semester course covering mechanics and thermal physics. Section 4 discusses Volume II, *Electric & Magnetic Interactions*, which corresponds to a typical second semester course, covering E&M and waves and physical optics. Since the essence of a curriculum lies in the tasks students are asked to do, to give a sense of the texture of the course there are detailed examples of some of the homework problems, and their contexts.

Section 5 discusses the research basis of the curriculum, which includes both formative and summative research.

Sections 6, 7, and 8 deal with the implementation of this curriculum. Section 6 briefly describes a particular classroom environment at NCSU. Section 7 lists the extensive set of resources available to instructors who adopt this curriculum, and section 8 discusses known issues that may arise for adopters.

2. Changing the content and emphasis of the introductory course

Matter & Interactions is a curriculum that represents a radical change in the ***content and emphasis*** of the calculus-based introductory physics course. Almost all physics education research has taken the curriculum content as an immutable given and focused on how to improve the pedagogical approach, in order to improve learning of the canonical curriculum. However, many physicists feel that the traditional curriculum content, which has remained essentially unchanged for over fifty years, is out of date, inappropriate, and inauthentic to the nature of the contemporary physics enterprise. The science and engineering students who take introductory physics courses will be working on problems such as the design of new conducting materials, fast, high density data storage and retrieval, new communication technologies, nanoscience and nanotechnology, alternative power sources, quantum computing, computer drug design, and computer modeling of extremely complex systems including climate and geophysical phenomena. These students need physics for the 21st century, not the 19th.

Physics is characterized by the search for deep, fundamental principles. The power of physics is based on the idea that from a small number of fundamental principles it is possible to predict and explain a broad range of phenomena. However, despite the intent of physics instructors and textbook authors, many students perceive the calculus-based introductory physics course to consist of a large number of special-case formulas, each specific to a very narrow range of situations. In the typical course students are not asked to analyze novel situations but rather to make small changes to previously solved problems. The emphasis is on specific solution patterns rather than on reasoning from powerful, universal principles. As a result the course appears to offer a collection of unrelated topics, rather than a unified framework for understanding the world.

The traditional calculus-based introductory physics course is all classical, all macroscopic, with anonymous, featureless objects of mass m and charge q. The theory expounded in lecture is often disconnected from the experiments done in the lab. There is no computational physics, despite the fact that contemporary physics now involves the interplay not only of theory and experiment but also of computation. The traditional course fails to connect to contemporary topics.

A look at the introductory biology course offers some perspective on the problem, as this course naturally incorporates the profound insights of the twentieth century such as the nature of DNA and viruses. In contrast, the introductory physics course nearly or completely eliminates all references to the physics of the twentieth century. How did this come to pass?

It used to be that engineering and science students were required to take three or four semesters of introductory physics, and the last course in the sequence typically had twentieth-century content. It would have been far better for a contemporary view of physics to have been integrated throughout the sequence, but at least there was some at the end. For various reasons, the number of required semesters was cut back to two almost everywhere, and the contemporary content was lopped off with little or no change to the initial semesters. Only physics majors now are required to learn about contemporary physics from physicists. Yet students in engineering and in other sciences need the insights of twentieth-century physics in order to thrive in their own disciplines, and the physics community owes these students a serious introduction to a contemporary view of the world.

Even the physics majors are short-changed by current practice. They come to the introductory courses curious about black holes, quantum phenomena, superconductivity, etc., all the wonderful topics they see in the mass media that inspired them to major in physics. Then they are offered more inclined planes. Many students reluctantly turn away, disappointed.

2.1 The goals of Matter & Interactions

One of the central results of physics education research has been the finding that effective teaching and learning do not come easily, and require a significant investment of effort and time on the part of both instructors and students. Physics education researchers have developed a variety of improved pedagogical approaches that do in fact improve students' learning of the traditional introductory physics topics. However, it is important to ask what educational goals are worth such an investment of time and effort. What should students learn in the introductory course? A clear set of educational goals needs to be articulated, not just a list of physics topics.

The goal of the M&I curriculum is to engage students in the contemporary physics enterprise, by emphasizing:

- A small number of fundamental principles, from which students start analyses
- The atomic nature of matter, macro/micro connections, and basic aspects of relativity
- Unification of topics, facilitated by the emphasis on fundamental principles and the atomic view of matter
- Modeling complex, real physical systems, including computational modeling

Students who have completed the introductory calculus-based physics course should see clearly that a small number of fundamental principles can explain a very wide range of phenomena; this should be a central goal of the course. Students should learn to feel capable of applying fundamental principles to new problems. They should see the place of classical physics in the larger physics framework (including the atomic nature of matter, quantum mechanics, and relativity), and they should have experience with semiclassical analyses.

In contrast, the traditional rationale given for introductory physics is to have students learn systematic problem solving, learn to separate the world into system and surroundings, and practice applying mathematics. Little *effective* attention is given to the larger goal of bringing students to see the unity of physics and the power of a small number of fundamental principles. Textbook authors and physics instructors have this reductionist nature of physics in mind, but the way in which the course usually plays out is such as to confirm in most students' minds the conviction that physics consists of a large number of disconnected special-case formulas.

2.2 Brief description of *Matter & Interactions*

The textbook *Matter & Interactions*[1] is structured to make clear to science and engineering students that there is a small number of fundamental principles, which the students themselves can employ to analyze a broad range of complex, messy, real-world phenomena. In mechanics, these are the momentum principle (Newton's second law in its more general form), the energy principle, the angular momentum principle, and the fundamental assumption of statistical mechanics. In electricity and magnetism there are added conservation of charge and the field concept, as expressed in Maxwell's equations. This emphasis on fundamentals and a microscopic model of matter permits the integration of topics that have traditionally been kept completely separate. For example, mechanics and thermal physics are intertwined. Electrostatic and circuit phenomena are analyzed using the same concepts and principles for both topics. Students are continually asked to analyze new situations, different from ones they have seen before, by starting from fundamental principles.

In addition to its emphasis on starting from fundamentals, the *Matter & Interactions* (M&I) curriculum is modern throughout. From the beginning, it emphasizes the atomic nature of matter, and does not relegate atoms to a final chapter that no one has time for. Students themselves engage in building physical models of messy real-world phenomena, including making idealizations, simplifying assumptions, approximations, and estimates, instead of solving only sanitized problems in which all such modeling has been done silently by the textbook author.

As a part of the modeling process, students write computer programs to model and visualize mechanical systems and fields in 3D using VPython (http://vpython.org) as an introduction to computational physics, which has become an equal partner to theory and experiment in the contemporary physics enterprise. Details of the mechanics course are described in Chabay and Sherwood (2004),[2] and aspects of the integration of mechanics and thermal physics are described in Chabay and Sherwood (1999).[3] Details of the electricity and magnetism course are described in Chabay and Sherwood (2006).[4] For additional information about the textbooks and curriculum, see http://www4.ncsu.edu/~rwchabay/mi.

3. Content, sequence, and emphasis of Matter & Interactions Volume I: Modern Mechanics

In the traditional calculus-based introductory physics course the fundamental concepts of mechanics are introduced quite late, and consequently are not seen by the student as having central importance. In a typical introductory textbook force is introduced in chapter 5, energy in chapter 7, momentum in chapter 9, and angular momentum in chapter 12. Consequently, what students often see as the most fundamental principle in all of physics is $x = \frac{1}{2}at^2$, the formula they have used the most.

In the M&I version of mechanics, *Modern Mechanics*, the fundamental principles are introduced much earlier than has traditionally been the case. Relativistic momentum is introduced in chapter 1 and the momentum principle (the more general form of Newton's second law) is introduced in chapter 2 and used from then on. The energy principle is introduced in chapter 4. This in itself makes the fundamental concepts and associated principles stand out as truly central to the enterprise.

In the traditional curriculum, the momentum principle (Newton's second law) is not actually central. In its general form, it is introduced very late in the course. In *Matter & Interactions* it is introduced in chapter 2 in the form $\vec{p}_f = \vec{p}_i + \vec{F}_{\text{net}}\Delta t$ (for sufficiently small time intervals), where $\vec{p} = \gamma m\vec{v}$. The concept of momentum, and the idea that for a known force law the motion of objects can be predicted into the future in an open-ended fashion, is central to the entire mechanics course. The Newtonian Synthesis is introduced: initial conditions plus the momentum principle plus a force law make possible an iterative update of momentum and position, showing the time-evolution character of the momentum principle. This picture contrasts with the understandable perception of students that $F = ma$ is essentially an algebraic statement of proportionality, with no sense of time evolution. Students carry out one or two steps of the Newtonian Synthesis on paper, then write computer programs to study planetary orbits, spring- mass oscillators, and scattering.

Two papers (refs. 2 and 3) discuss in detail the sequence of topics in *Modern Mechanics*, the first semester of the two-semester *Matter & Interactions* sequence. Briefly, the sequence in the *Modern Mechanics* volume of the textbook is this:

- Vectors in 3D; velocity and momentum

- The momentum principle (the generalized version of Newton's second law)
- Iterative momentum and position update with changing forces; gravitational and electric interactions
- The ball-and-spring model of solids; contact forces; curving motion; speed of sound, the harmonic oscillator
- The energy principle; role of the choice of system in the energy principle
- Quantized energy
- Multiparticle systems; center of mass motion, motion about the center of mass
- Momentum conservation in multiparticle systems: collisions; Rutherford scattering
- The angular momentum principle
- Quantum statistical mechanics; the Einstein solid; the Boltzmann distribution
- Kinetic theory of gases
- Heat engines as an application of entropy

3.1 Teaching students to start from fundamentals

It is important that students be able to approach problems of a kind they've never seen before. This requires starting from a fundamental principle rather than using a solution from some previously solved problem or grabbing a tertiary derived formula. The idea of starting every analysis from a fundamental principle is a new one to most students, whose previous schooling has stressed memorizing formulas to be used in particular kinds of problems. Often the students have been taught to start with a formula that contains the quantity of interest to the left of an equals sign, so it is not obvious how they could obtain a solution (the desired quantity) by starting from a general principle that may not explicitly contain the desired quantity. Part of the instruction and acculturation necessarily involves explicit teaching of what it means to start from a fundamental principle, and how to move from the general statement of the principle to a detailed analysis using information particular to a specific situation.

3.2 Examples of large problems involving modeling

Here are some examples of real situations which students have been asked to analyze, with varying degrees of support and scaffolding, depending on the prior preparation of the particular group of students.

Applications of the momentum principle

- Running students collide (find the force of one student on the other)
- NEAR spacecraft encounters Mathilde asteroid (determining density of an asteroid)
- Finding dark matter (how Vera Rubin discovered this in galaxies)
- Black hole at galactic center (find the mass from the orbits of nearby stars)

Applications of the momentum principle plus the atomic nature of matter (ball-and-spring model of solid)

- Macro-micro connection: Young's modulus yields interatomic spring constant k_s
- Model propagation of sound in a solid; determine speed of sound
- Diatomic molecule vibration: estimate the frequency from interatomic k_s
- Quantum statistical mechanics of the Einstein solid at the end of the mechanics course: students fit data for the low-temperature heat capacity using k_s obtained from Young's modulus

Applications of the energy principle

- Fusion analysis: energy input required for fusion, and net energy gain
- Fission analysis: final speeds and initial separation for symmetrical fission fragments
- Design a bungee jump apparatus
- Complete analysis of jumping up from a crouch

The problem statement concerning the NEAR spacecraft mission is shown in figure 1. The problem statement for analyzing fission is shown in figure 2. Part (c) of the fission problem is intended to show that a simple model of fission in which the fission fragments start from rest, nearly touching, works rather well.

These homework problems deliberately transcend the traditional narrow restrictions of introductory mechanics. In the 21st century it is inappropriate to teach classical mechanics in isolation. Classical mechanics needs to be embedded in the larger context of thermal physics, relativity, and quantum physics to be authentic to contemporary physics, which is often semiclassical. After a traditional mechanics course, a math major in the E&M course said, "Last semester they presented mechanics as a closed axiomatic system. I thought I had learned something of universal validity, and I felt betrayed when I found that wasn't true. I appreciate an axiomatic treatment in math courses, but that's not appropriate in a physics course."

In 1997 the NEAR spacecraft passed within 1200 km of the asteroid Mathilde at a speed of 10 km/s relative to the asteroid (http://near.jhuapl.edu). Photos transmitted by the spacecraft show Mathilde's dimensions to be about 70 km by 50 km by 50 km. It is presumably composed of rock; rock on Earth has an average density of about 3000 kg/m^3. The mass of the NEAR spacecraft is 805 kg.

(a) Sketch qualitatively the path of the spacecraft.

(b) Make a rough estimate of the change in momentum of the spacecraft resulting from the encounter. Explain how you made your estimate.

(c) Estimate the deflection (in meters) of the spacecraft's trajectory from its original straight- line path, one day after the encounter.

(d) From actual observations of the position of the spacecraft one day after encountering Mathilde, scientists concluded that Mathilde is a loose arrangement of rocks, with lots of empty space inside. What about the observations must have led them to this conclusion?

Fig. 1: Problem statement concerning the NEAR spacecraft mission.

Uranium-235 fissions when it absorbs a slow-moving neutron. The two fission fragments can be almost any two nuclei whose charges Q_1 and Q_2 add up to 92e (where e is the charge on a proton), and whose nucleons add up to 236 protons and neutrons (U-236; U-235 plus a neutron). One of the possible fission modes involves nearly equal fragments, palladium nuclei with $Q_1 = Q_2 = 46e$. The rest masses of the two palladium nuclei add up to less than the rest mass of the original nucleus. (In addition to the two main fission fragments there are typically one or more free neutrons in the final state; in your analysis make the simplifying assumption that there are no free neutrons, just two palladium nuclei.) The rest mass of the U-236 nucleus is 235.996 u (unified atomic mass units), and the rest mass of each Pd-118 nuclei is 117.894 u, where 1 u = 1.7×10^{-27} kg (approximately the mass of one nucleon).

(a) Calculate the final speed *v*, when the palladium nuclei have moved far apart (due to their mutual electric repulsion). Is this speed small enough that $(1/2)mv^2$ is an adequate approximation for the kinetic energy of one of the palladium nuclei? (It is all right to go ahead and make the nonrelativistic assumption first, but you then must check that the calculated *v* is indeed small compared to *c*.)

(b) Using energy considerations, calculate the distance between centers of the palladium nuclei just after fission, when they are starting from rest.

(c) A proton or neutron has a radius of roughly 1×10^{-15} m, and a nucleus is a tightly packed collection of nucleons. Experiments show that the radius of a nucleus containing *N* nucleons is approximately $\left(1.3\times10^{-15}\text{ m}\right)\times N^{1/3}$.What is the approximate radius of a palladium nucleus? Draw a sketch of the two palladium nuclei in part (b), and label the distances you calculated in parts (b) and (c).

Fig. 2: Problem statement for analyzing fission.

3.3 Integration of topics

The emphasis on starting from fundamental principles, and the stress on an atomic view of matter, makes possible the integration of topics which traditionally are presented as disconnected subjects. This section describes an example of such integration: the integration of mechanics and thermal physics.[3] Like other topics in the course, these subjects are presented in such a way that the limitations of the purely classical treatments are clear, and the articulation of classical physics with quantum and relativistic physics is exposed.

3.4 Macro-micro connections and the integration of mechanics and thermal physics

It is a peculiar feature of the traditional introductory curriculum that classical mechanics and thermal physics are taught as separate subjects. The first law of thermodynamics, for example, is often presented as though it were completely separate from the energy principle encountered in mechanics. However, classical mechanics alone, without the addition of thermal physics, cannot explain various common everyday phenomena. For example, if you drag a block across the table at constant speed, it would seem that no net work is done on the block, yet the block’s temperature rises, and evidently there is an increase in the internal energy of the block.[5] Does this mean that the energy principle applies only to situations where thermal effects are negligible? Can one really claim that it is a powerful fundamental principle that applies to all situations?

The M&I curriculum intertwines mechanics and thermal physics, by taking a viewpoint that emphasizes the atomic nature of matter. The ball and spring model of a solid is introduced early in the mechanics course. Students hang weights from the end of a long thin wire and measure Young's modulus (figure 3), then interpret this phenomenon in terms of the ball and spring model of a solid metal. Through a semiclassical macro-micro argument one obtains from Young's modulus the effective stiffness of the spring-like interatomic bond.

Students measure the spring stiffness and period of a macroscopic spring-mass system, then write a computer program to carry out a numerical integration of the momentum principle applied to this system, using their measured mass and spring stiffness. They find good agreement between the period of the computer model and the period they measured. They also study the effects of initial conditions on 3D oscillations. (See section 3.6 and figure 7.) Students also study the analytical solution for the motion.

Next there is presented a microscopic model of an aluminum rod, considered as a chain of aluminum atoms connected by interatomic “springs,” whose stiffness the students previously determined from Young's modulus for aluminum (see figure 4, the lecture-demo program 03_speed_of_sound.py, available at http://www4.ncsu.edu/~rwchabay/mi). By displacing an atom and observing the propagation of the disturbance through the chain of atoms in the model, it is possible to obtain a numerical prediction for the speed of sound, which agrees quite well with the measured speed of sound in aluminum obtained by a time of flight demo or lab experiment (strike one end of an aluminum bar, which triggers a scope, and time the onset of a pulse from a microphone at the other end of the bar). This analysis is repeated to find the much smaller speed of sound in lead. It is a striking example of the power of the fundamental principles of physics, plus a simple model for the atomic nature of matter, that hanging weights on the end of a wire leads to predicting the speed of sound!

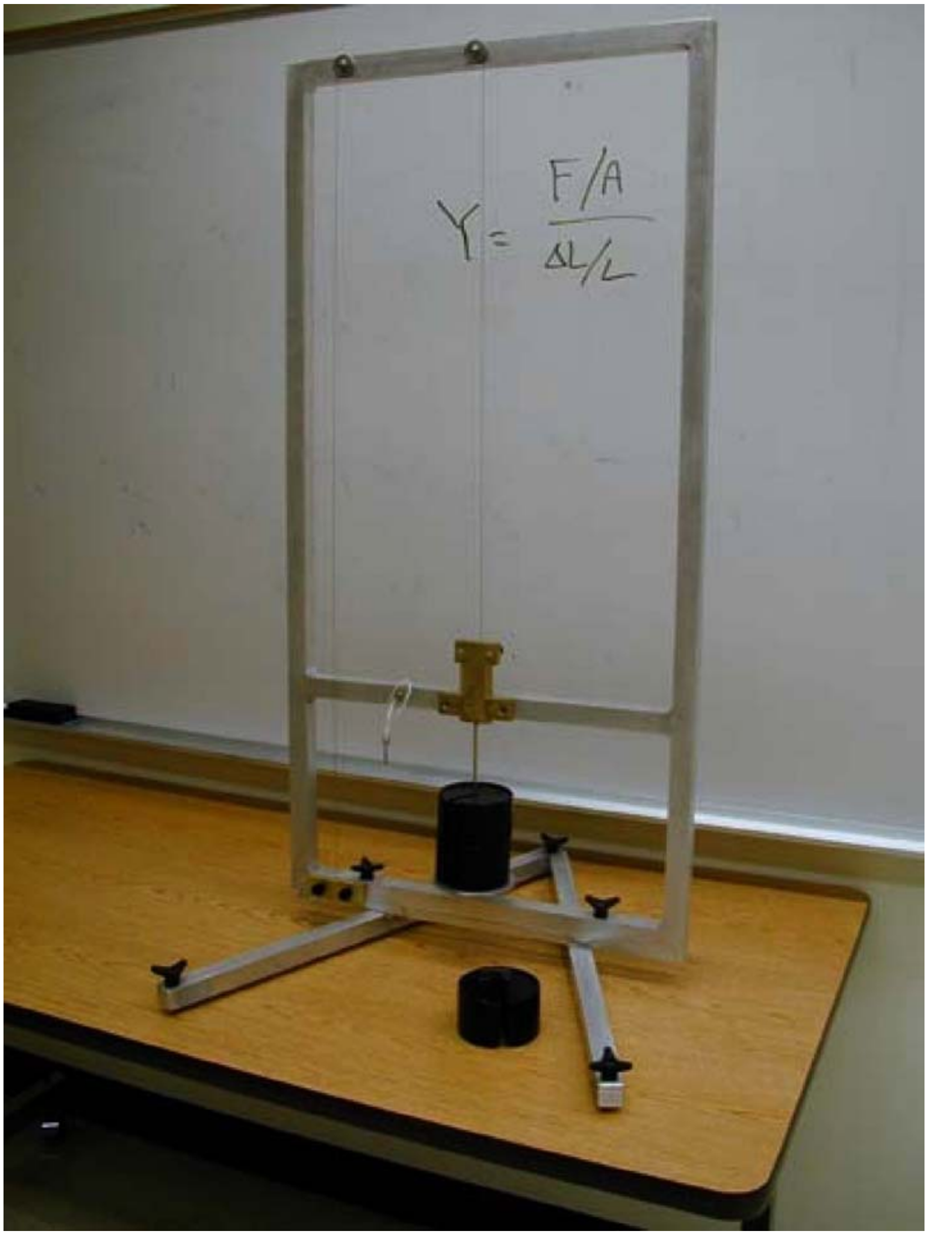


Fig. 3: An apparatus used by students to measure Young’s modulus.

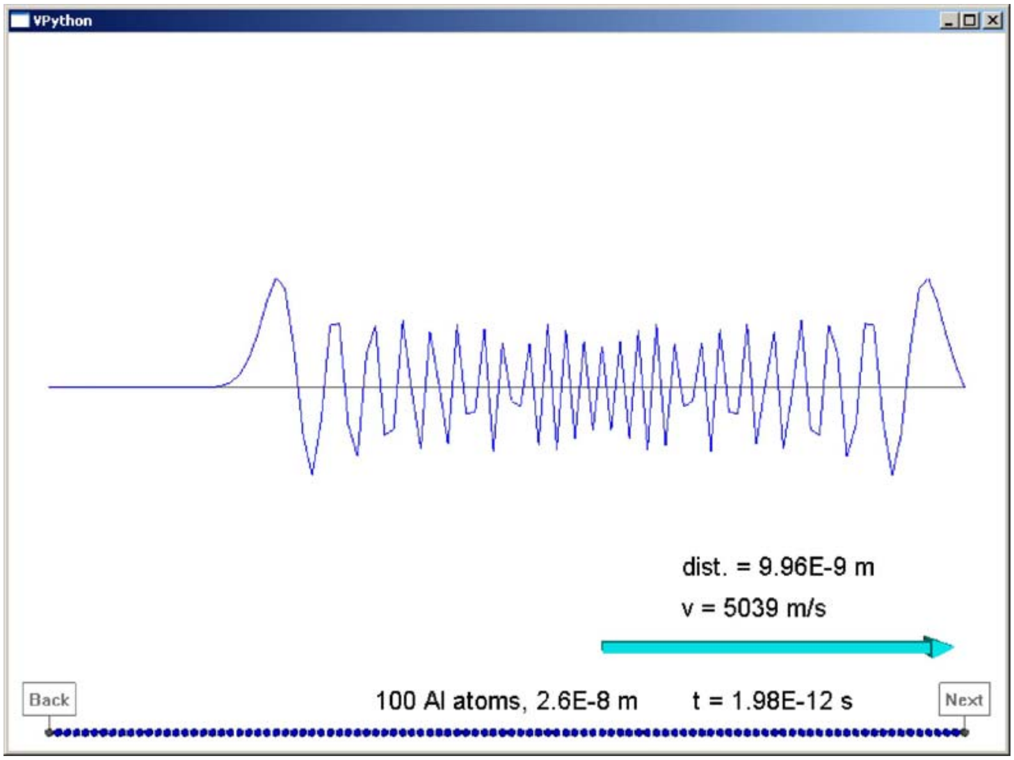


Fig. 4: A lecture-demo program showing the propagation
of a disturbance along a chain of aluminum atoms.

As a result of this experience with the ball and spring model of a solid, when the energy principle is introduced it is natural to include the thermal energy of a macroscopic object, which is simply energy associated with the microscopic kinetic and potential energy of the atomic balls and springs making up the solid. Thermal energy is always considered along with other energy terms in the application of the energy principle to macroscopic systems.

Since most students have previously encountered the idea of discrete electronic energy levels in their chemistry courses, it is a relatively easy step to discussing quantized electronic, vibrational, and rotational energy levels, and photon absorption and emission, in a variety of atomic systems. No attempt at this stage is made to discuss wave functions, superposition, or the relation of wavelength to photon energy. It is stated without proof that the quantized harmonic oscillator has evenly spaced energy levels, and students work through several exercises and problems that deal with this system.

With this preparation, a quantum statistical mechanics analysis of the Einstein solid is introduced, a ball and spring model in which each atom is modeled as three independent quantized oscillators (Moore and Schroeder).[6] Confirming what was found by Moore and Schroeder, on quizzes and tests most students are able to analyze the Einstein solid quite competently. Students also write computer programs to calculate the entropy, temperature, and heat capacity of nanoparticles of aluminum and lead. They are asked to fit their curves for heat capacity as a function of temperature to actual experimental data for aluminum and lead, by adjusting one parameter, the effective stiffness of the interatomic "spring". When a stiffness that is consistent with the value of Young's modulus is used, the curves fit the experimental data quite well (figure 5).

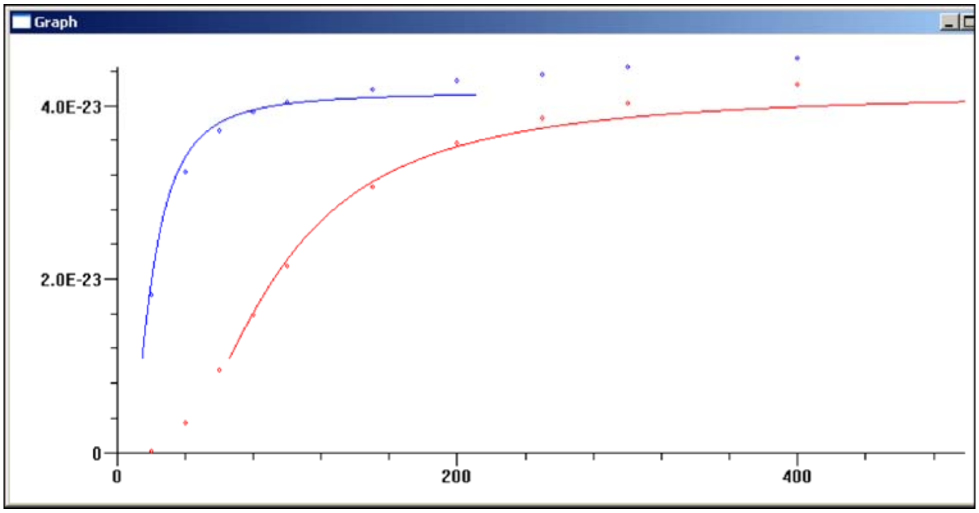


Fig. 5: Student calculation of heat capacity per atom as a function of temperature for lead (blue) and aluminum (red), superimposed on experimental data points.

This climax to the mechanics portion of the course is a striking illustration of the power of fundamental physics principles and atomic models of matter. The students can see that from measuring the stretch of a wire due to hanging weights, they gain sufficient information to predict both the speed of sound and the temperature dependence of the heat capacity of the metal, two properties that initially look totally unrelated to the original measurement.

3.5 Classical physics in the larger context

Since so many contemporary applications of science and technology are based on 20th century physics, it is important that students completing an introductory physics course, whether or not they will continue to study physics, see the relationship of classical physics to modern physics. In the M&I curriculum the principles of mechanics and E&M are not narrowly restricted to their limited classical formulations but are visibly embedded in a larger physics context. Momentum and energy are treated relativistically from the start. Students work homework problems on fission and fusion in which the rest masses change. Quantized energy is introduced to help students link the nature of energy at the macroscopic level to the behavior of energy in the world of atoms.

In the E&M semester, the reality of electric field is made manifest through discussions of retardation effects, in which the field of a remote positron and electron can affect matter for a while even after the remote source charges have annihilated each other. Retardation also plays a role in the transient that leads to the steady state in a simple circuit. A thought experiment involving the mutual repulsion of two protons, viewed from two different reference frames, shows that time must run at different rates in the two frames. All of these discussions serve to situate E&M in a larger context than would otherwise be the case.

3.6 Computational physics

The M&I curriculum gives students a significant introduction to computational physics. In the past, the physical sciences and engineering could be characterized as involving theory and experiment and the interplay between the two. Now however these disciplines involve theory, experiment, and computation, and the interplay among all three. Just as it would be inappropriate for the introductory course to consist solely of theory, or solely of experiment, so in the 21st century it would be inappropriate not to include a serious computational component in the course.

Moreover, computation provides insights that are hard to obtain any other way. In mechanics, the traditional curriculum emphasizes closed form solutions (e.g. circular motion at constant speed) and situations where the motion is at least partially known and some of the forces are deduced from the motion (e.g. the force of an incline on a sliding block). Unless students themselves are able to predict motion by repeatedly updating the momentum and position, given a force law, it is unlikely that they can acquire a sense of the real power of the Newtonian Synthesis. Uri Ganiel reports that when his group at the Weizmann Institute in Israel was developing a unit on chaos, they assumed students already had a deterministic view of classical mechanics.[7]

They found, however, that students who had experienced the traditional treatment of introductory mechanics did not in fact have such a view. The group had to create a module on determinism to precede the material on chaos.

The introduction of computation and numerical integration also makes it feasible for students to analyze situations that are not accessible analytically at the introductory level, such as elliptical orbits, and thereby to transcend the view of mechanics as consisting of a small number of analytical solutions. In E&M, computation permits the visualization of fields in three dimensions, something of particular importance in the case of magnetic fields.

It is desirable that students themselves write the computer programs so that there are no impenetrable “black boxes.” Fortunately, modern computers are fast enough that the simplest first-order algorithms can be made sufficiently accurate simply by choosing a small step size. This makes it unnecessary in this introduction to computation to teach the details of numerical analysis, which can be left to a later course in computational science.

It is also desirable that students produce 3D animations of physical systems, and of electric and magnetic fields, not just graphs, but in standard programming environments this has been very difficult to do, and students in the introductory calculus-based physics course are very knowledgeable about all uses of computers save one: programming. Roughly half of the engineering and science students at NCSU have never written a computer program before coming to the mechanics course. There isn’t time to teach programming, much less how to do 3D graphics, so it is essential to have a suitable programming environment that requires very little instruction. VPython (http://vpython.org) provides an appropriate environment for the purpose. VPython is built on the modern, object-oriented Python programming language, and like Python is open-source, multiplatform freeware.

Here are two examples of programs students have written. Figure 6 shows a restricted three-body orbit of a spacecraft moving near a stationary Earth and stationary Moon. Many students were surprised and pleased when their repetitive updates of momentum and position gave this unusual fish-like trajectory for a particular set of initial conditions (spacecraft launched upward, to the left of the Earth). This is a nice example of complex behavior emerging from (relatively) simple physical principles, in this case the momentum principle plus the gravitational force law. This illustrates the power of fundamental physics principles and gives a graphic example of the time-evolution character of the momentum principle. Students were also led to see that although the trajectory is an example of classical determinism, it is extremely sensitive to the initial conditions, which hints at one of the important aspects of chaos.

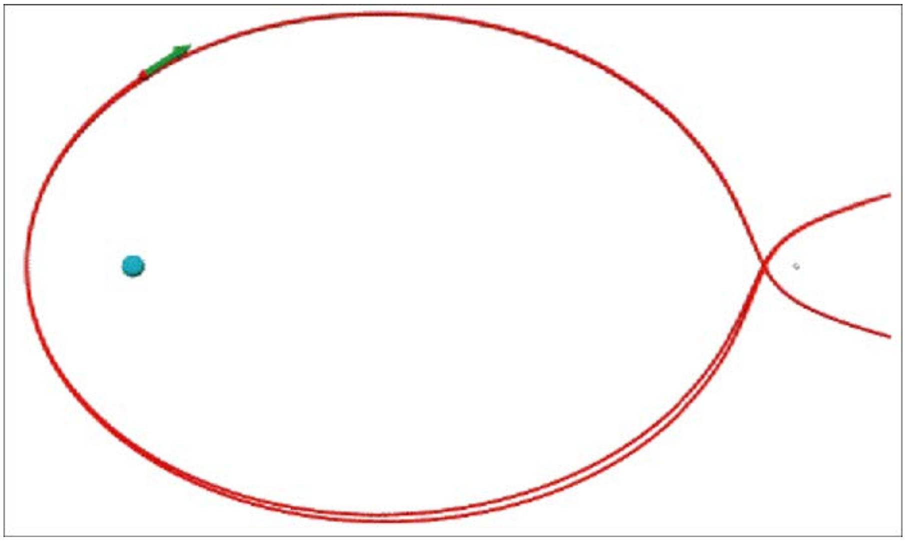


Fig. 6: Restricted three-body program written by a student: a spacecraft moving near a stationary Earth and stationary Moon.

Figure 7 represents the 3D motion of a mass hanging from a spring. Again, many students were pleased to find their simple programs generating such complex and beautiful behavior.

VPython was created in 2000 by David Scherer, a student in the *Matter & Interactions* course at Carnegie Mellon, who had the brilliant and highly original idea to make navigable 3D animations a side effect of physics computations. While one's calculations are running (say, to continually update the momenta and positions of a binary star system), a parallel thread periodically creates a 3D image in OpenGL corresponding to the current attributes of objects declared by the student (in this case, two spheres). The effect is that without any explicit graphics statements in the computational loop, there appears a window with a navigable 3D animation of the motion of a binary star.

VPython supports standard vector computations, so students can write their calculations in vector form. This has the important side benefit of helping students to view vectors as powerful tools for analysis rather than as unpleasant trigonometry to be avoided.

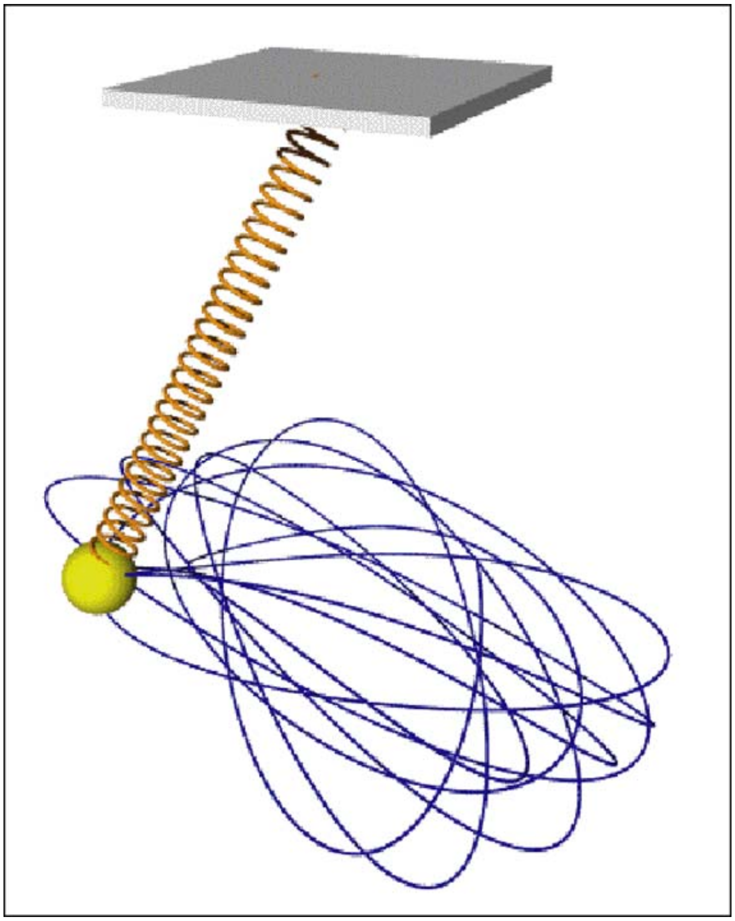


Fig. 7: 3D motion of a mass hanging from a spring, leaving a trail.
The program was written by a student.

4. Content, sequence, and emphasis of Matter & Interactions Volume II: Electric & Magnetic Interactions

In the electricity and magnetism (E&M) segment of the traditional introductory calculus-based physics course, many new and increasingly abstract concepts, embodied in complex formal relations, are introduced at a rapid pace. As a result, many students find E&M significantly more difficult than classical mechanics. Chabay and Sherwood (2006) describe a different intellectual structure for the E&M course that stresses conceptual coherence, connects the abstract field concept to concrete microscopic models of matter, and follows a clear story line, culminating in the classical model of the interaction of electromagnetic radiation and matter.[4] This sequence has proven to be effective in teaching the basic concepts of E&M.

4.1 Why is E&M difficult for students?

Because electromagnetic interactions play a central role in determining the structure of the natural world and are the foundation of most current and emergent technology, a basic understanding of electricity and magnetism is important. Traditionally, science and engineering students are introduced to E&M in the second half of the introductory calculus-based physics course, after they have completed an introduction to classical mechanics. However, even students who have done well in the first part of the course often find E&M to be difficult and confusing.

In E&M students encounter for the first time a level of abstraction and mathematical sophistication far beyond what they have experienced. In mechanics many situations involve familiar macroscopic objects: balls and sticks, cars and airplanes. At least some important concepts, such as velocity and force, are easily related to everyday experience. In E&M the student is quickly introduced to a world in which almost all of the quantities are invisible; they are either microscopic such as electrons or abstractions such as field, flux, and potential. Integral calculus becomes a central mathematical tool, and students are asked to apply it in unfamiliar ways, such as calculating the path integral or surface integral of a quantity expressed as a vector dot product. For the first time, it is necessary for students to think and visualize in three dimensions, a skill they have never before practiced. The role of symmetry and the nature of a symmetry argument as used in E&M are alien to students who have invested hundreds of hours in algebraic reasoning, but who have little experience with topology or with formal logical reasoning.

In the traditional introductory E&M sequence, the usual approach to this onslaught of new concepts and ways of reasoning is to gloss over it, going through the fundamentals at high speed, and spending most of the course on rote problem solving. The conceptual and mathematical complexity of the field is exacerbated by the extraordinarily rapid introduction of a long sequence of new and increasingly abstract concepts. The ideas of charge, electric force, field, flux, and Gauss's law are often presented within the first couple of weeks of the course. These ideas are quickly followed by the concepts of potential, potential difference, and electric current, which appear to be only slightly related to the previous set of concepts. Students can easily be overwhelmed by this rapid introduction of abstract ideas and usually are not given sufficient practice to be able to apply these concepts reliably, nor to discriminate them from each other. By the end of the course, even good students may have forgotten the expression for the electric field of a single point charge, because it has not been used for many weeks. Students who can reliably solve complex circuit problems often believe at the end of the course that electrons are used up in light bulbs or that the current produced by a battery is independent of the circuit it drives.[8,9] The rapid introduction of new concepts and escalation in complexity frequently confirms in students' minds the conviction that physics consists of a large number of disconnected formulas.

4.2 Goals of the introductory E&M sequence

Some research and development in physics education has focused on remedying particular problems with this sequence, by giving students additional focused practice on one concept or another. Here the choice instead is to re-examine the intellectual structure of the E&M curriculum, in an attempt to identify which concepts are centrally important, how these concepts are related, and how they may be introduced to students in a coherent, comprehensible sequence. The overall goals are those of the *Matter & Interactions* curriculum, as explained earlier.

4.3 Content, sequence, and emphasis

The goals of the new sequence are to increase conceptual coherence, give students time to assimilate and master new concepts, add concreteness, and help students to develop microscopic models that facilitate reasoning about complex systems. The organization of topics is hierarchical, and the overarching theme of the entire sequence is the field concept. The sequence is organized into four large segments:

Stationary charges

- Electric field
- A microscopic model of matter (conductors and insulators)
- Effect of electric field on matter; the approach to equilibrium
- Electric field of distributed charges
- Electric energy and electric potential

Moving charges

- Magnetic field
- Microscopic view of circuits (charge, field, energy, and the potential in DC and RC circuits)

- Macroscopic view of circuits
- Magnetic force; microscopic view of magnetic forces on currents

Reasoning about patterns of field in space

- Gauss’s law and Ampere’s law

Time-varying fields and accelerated charges

- Faraday’s law
- Maxwell’s equations; electromagnetic radiation; classical interaction of light and matter
- Physical optics; wave-particle duality

For details on this sequence, see ref. 4. The next few subsections give a summary of the basic issues.

4.4 Field: An intermediate level of abstraction

The concept of field is central to electricity and magnetism. In the traditional introductory course this concept is not used during large sections of the course, including the sections dealing with electric circuits and Faraday’s law. Consequently, the field concept does not appear central to students. A goal of the redesigned topic sequence is to make the field concept appear more important, comprehensible, and useful to the students.

4.5 Magnetic field

In the traditional sequence magnetic field and magnetic force are introduced late in the course, after electrostatics and circuits. This delay has many disadvantages. The rapid introduction of both magnetic field and magnetic force makes both concepts difficult to assimilate, because they involve vector cross products and require difficult mental rotations. Students have little remaining time in the course to gain adequate experience with the topic and little time to compare and contrast electric and magnetic fields and their effects.

4.6 Effects of fields on matter

As in *Modern Mechanics*, the E&M section of the curriculum emphasizes the atomic nature of matter. Fields by themselves are very abstract, but experience with fields comes from observing their effect on material objects. In the traditional curriculum polarization phenomena are often briefly mentioned, presumably because atoms and their constituent particles are not discussed, so reasoning about these complex phenomena is difficult. In the new approach the polarization of salt solutions, metals, molecules, and insulating solids are discussed in detail, with reference to simple microscopic models of atoms and molecules and especially of solids.

4.7 Macro-micro connections and the integration of electrostatics and circuits

The analysis of electric circuits provides an opportunity to solidify the new concepts that have been introduced (charge, electric field, potential, magnetic field, models of matter). However, in the traditional E&M curriculum electrostatics and circuits are treated as almost completely separate topics. Electrostatic phenomena are analyzed in terms of charge and field, while circuits are analyzed in terms of current and potential, and the connection between these two sets of concepts is not made salient. This dissociation can reinforce the perception that physics consists of a large number of special case formulas. In addition, this approach removes the concept of electric field from the student's view, so that by the end of the course students might have forgotten most of what they learned about the concept of electric field in the beginning of the course.

To stress the fundamental nature of the field concept and the microscopic view of matter, both DC and RC circuits can be analyzed from a microscopic point of view in terms of the electric field and the microscopic properties of conductors. The key concept is that a gradient of surface charge density along a wire is the source of the electric field in the wire that drives the current. This model has been discussed for many years[10,11] but has rarely been mentioned in introductory textbooks. For an extensive bibliography, see Preyer.[12] Haertel's monograph points out the explanatory power of this model.[13] We discuss the M&I presentation of the surface charge model in detail in ref. 4.

4.8 Patterns of field in space: Gauss's law

In the traditional sequence Gauss's law is introduced very early, sometimes during the first week of the course. Generations of physics teachers have lamented the fact that the students don't understand Gauss's law. From a cognitive point of view it is clear why this lack occurs despite the best efforts of good teachers. At the beginning of the course, many students are struggling with what is for them a subtle distinction between charge and field, yet Gauss's law embodies a complex topological relationship between charge and patterns of field in three-dimensional space. Early in the course students have had no experience with the kinds of patterns of field that are possible in space, but these patterns of field lie at the heart of the topological relationship.

The shakiness of the concepts of charge and field, the students' lack of experience with possible field configurations, their lack of mathematical background with respect to surface integrals, and their unfamiliarity with symmetry arguments make the introduction of Gauss's law early in the course a frustrating endeavor. Because it poses such conceptual challenges for students, it is appropriate to delay the introduction of Gauss's law until about two thirds of the way through the course, when students have had much experience with patterns of electric (and magnetic) fields in different contexts, including in electric circuits.

4.9 Faraday's law

Faraday's law is usually difficult for students. It involves a dynamic connection between magnetic and electric phenomena and is traditionally introduced when students have had only a rather brief exposure to magnetic fields and when the electric field concept has not recently been used. Moreover, the integral form (which is the usual form introduced in the introductory course, because most students have not yet encountered divergence and curl in their calculus courses) involves the concept of flux, which is traditionally introduced at the start of the course in the context of Gauss's law and not mentioned again until the introduction of Faraday's law. The effect is to use a forgotten concept (flux) to relate a line integral of electric field (emf) to the time derivative of a surface integral of a quantity with which the students have had inadequate practice (magnetic field). It is not surprising that Faraday's law is usually difficult for students.

In M&I Faraday's law has a better foundation thanks to long experience with magnetic field and recent experience with flux (in the context of Gauss's law). Also, the curly electric field is emphasized, not just its integral, emf. Motional emf is introduced in an earlier chapter on magnetic force to help students make an important distinction between two very different mechanisms for producing emf (magnetic force on moving charged particles versus a time varying magnetic field), which often are not clearly differentiated in the traditional sequence.

4.10 Electromagnetic radiation

After discussing Gauss's law for electricity and magnetism, Ampere's law, and Faraday's law, one is ready to consider Maxwell's extension to Ampere's law and show that crossed electric and magnetic fields can propagate in empty space at the speed of light. By using a qualitative version of an argument due to Purcell,[14] animated diagrams are used to show the results of retardation and make it plausible that an accelerated charge produces transverse radiative fields. The equation for the radiative fields of an accelerated charge may be stated without proof at this level. A sense of the mechanism for the production of radiation is important in making accessible the classical interaction of electromagnetic fields with matter, especially re-radiation. With a continual emphasis on the effects of fields on charged particles, it is natural to talk about the acceleration of the electrons in matter by the electric field in incident radiation and the subsequent re-radiation by these accelerated electrons. This view can bring to physical optics a clear sense of mechanism.

4.11 Minimalism and choice of representation: Field lines

Because of the many new concepts in E&M, it is important to take a minimalist approach and to consider carefully the cost of introducing still more concepts and representations. In this spirit field lines have been nearly entirely eliminated from the course. At the introductory level there are almost no problems in which students can use field lines to reason about some phenomenon, and a significant investment of instructional time and a significant amount of practice are required if students are to be expected to interpret field lines correctly. Students are rarely taught to construct field line diagrams quantitatively, so this representation never becomes a really useful tool for them. A full discussion of the physics and pedagogical reasons for eliminating field lines from the introductory course is given in ref. 4.

4.12 The transition from mechanics to E&M

Changes in the content and emphasis of the mechanics course can facilitate the transition from mechanics to E&M. As discussed earlier, in the M&I approach to mechanics students are given practice in starting from a small number of fundamental principles and in working with simple microscopic models of matter. Macro-micro connections in mechanics help students understand both macroscopic phenomena and microscopic phenomena. Along with gravitational forces and gravitational potential energy, electric force and electric potential energy are introduced and used routinely in the mechanics course. For example, a mechanics homework problem asks students to determine the required initial kinetic energy for a proton and deuteron to come into contact so they can fuse to give He^3 plus a photon; students also calculate the net energy gain in the fusion reaction. As a result, students beginning the E&M course have already had useful experience with electric interactions and microscopic models of matter.

Mark Haugan taught a highly accelerated version of M&I in the summer for colleagues and graduate students in preparation for expanding the use of the curriculum at Purdue from the honors course taken by physics majors to the big engineering course.[15] During the mechanics section of the curriculum one of his colleagues expressed some unease at what seemed an imbalance between macro and micro phenomena and analyses, with too much micro. But when they came to the E&M section, this same colleague observed with surprise and pleasure that usually there was a big jump in abstractness and difficulty when going from mechanics to E&M, but with the M&I sequence the connection was seamless and easy, thanks to the attention paid to the atomic nature of matter throughout the mechanics section.

5. Research informing the design of the curriculum

There are three facets to the research foundation on which this curriculum has been built. First, there is a body of basic research on learning, done by cognitive psychologists and cognitive scientists. This research has been done both in laboratory and in classroom settings. The work of some PER (physics education research) scholars has built on this work, focusing particularly on the learning of physics, and focusing on a classroom context.

Second, much formative research has been done in the process of developing the curriculum. These unpublished studies, some informal, some more formal, have been incorporated into the textbook through many revisions; some of the chapters of the textbook have been written, tested with students, and re-written as many as thirteen times.

Third, some summative research, comparing learning outcomes of this curriculum to the traditional curriculum, has been done by the developers and by others at other institutions who were not connected with the developers.

It is unfortunate that the large effort required to create the curriculum, test it, and implement it in big classes has meant a correspondingly smaller production of published research papers than one would have preferred, but at least the research has been incorporated into the curriculum in the form of a textbook and extensive additional resources for students and instructors, as will be discussed later.

5.1 Basic research on learning and problem solving

Thanks to the fortunate circumstance of working closely for many years with cognitive scientists and social psychologists during the development of the curriculum, the perspective on curriculum development was strongly informed by research on cognition and motivation in classroom learning. This perspective is reflected throughout the curriculum and supporting materials, and this section will make explicit some of the significant aspects of this influence.

Active processing: Research in cognitive science has shown that students who engage in active processing learn significantly more than students who read or listen attentively, but passively. Anderson[16] discusses the positive effects of elaborative processing (augmenting a to-be-remembered item with additional information) and deliberate practice (practice that involves monitoring how well one's performance corresponds to the correct performance). Chi and her colleagues[17] found that students who actively engaged in attempts to explain textbook problem solutions to themselves, and students who continually assessed their own understanding by attempting to predict the next step in a chain of reasoning, learned significantly more than students who simply read over the text and solutions carefully. Because novice physics students are usually not skilled at active reading of scientific textbooks, built into the design of the textbook are two features to help students learn to read actively. Within the text, students frequently encounter "stop and think" icons, highlighting questions that readers should try to answer themselves before going on to the discussion in the next paragraph. At the end of each section of the text students encounter a group of in-line exercises. These simple exercises, both qualitative and quantitative, require the student to apply the concepts covered in the preceding section. Answers to the exercises are available at the end of the chapter.

These basic findings have been reinforced by research from the PER community. Hake[18] has summarized a large body of assessment data showing that students' qualitative understanding of the Newtonian concept of force, as measured by the FCI,[19] improves as the amount of active engagement in their classrooms increases. Mazur[9] likewise found that students who actively thought about and debated ideas during lecture gained significantly more qualitative understanding of physics principles. This research focused on classroom dynamics rather than on textbook design; however it reinforces the goal of increasing students' cognitive activity during all phases of a course, including studying textbooks. As discussed in section 6, the implementation of M&I at NCSU employs a variety of techniques to encourage active engagement, including interactive lectures and small group studio sessions.

Primacy: Research in learning and memory has shown that people remember best the things they learn earliest and practice the most.[20] Taking this result seriously suggests that the most important ideas should be introduced at the beginning of a course, and should be used over and over. In M&I both the mechanics and the E&M sequences do exactly this. Because the momentum principle is central to classical mechanics, momentum and the momentum principle ($d\vec{p}/dt = \vec{F}_{\text{net}}$) are introduced in the first week of the course, and are used extensively throughout the course. In E&M, the electric field concept is introduced immediately, and is used throughout the course. Magnetic field is introduced much earlier than has been traditional, and is used throughout the remainder of the course.

Recency: Research also shows, not surprisingly, that learners remember concepts they have studied recently better than those they have studied previously, but not used recently.[20] In the traditional E&M sequence, the difficult concept of flux is introduced very early, then abandoned until students encounter Faraday's law many weeks later. In M&I, an added benefit of introducing Gauss's law late in the semester is the opportunity to follow Gauss's law immediately with Faraday's law, which also requires the flux concept.

Interference: There is, however, the danger of interference between similar concepts introduced in close succession.[16] The traditional curriculum sequence, in which kinetic energy and momentum are both introduced late in the mechanics semester, should therefore produce interference between these concepts, as has indeed been shown.[21],[22] Measurements (see below) suggest that this is decreased in the M&I sequence.

Transfer: An especially important finding that is well documented in the research literature is the small probability of "transfer" -- that is, of a learner applying concepts or techniques learned in one context to problems in a different context, even if that context appears similar to an expert. The difficulty of transfer, well documented in basic studies in psychology and education[16] has been confirmed in many PER studies (see below). The M&I emphasis and explicit instruction on how to start all problems from a small set of fundamental principles is in part intended to facilitate transfer by giving students the experience of applying the same principles and techniques to solve a wide variety of problems that on the surface appear very different.

Cognitive task analysis: One of the primary techniques applied in cognitive science is "cognitive task analysis." This refers to an analysis, at an exceeding fine grain size, of all the steps in reasoning that are required to solve a particular problem. In cognitive science, task analyses are frequently tested by writing computer programs to perform the task in question.[23] An adequate analysis is sufficiently fine grained if a computer programmed to execute these small steps can solve new (unfamiliar) problems. An example of a cognitive task analysis in physics is Reif's work on acceleration.[24,25] The restructuring of the sequence of topics in E&M grew from a detailed task analysis (see discussion of the E&M sequence in ref. 4).

Curiosity: Research on motivation and learning has identified three factors which contribute to students' intrinsic motivation to learn. Lepper & Malone identified these factors as "curiosity, challenge, and control."[26,27] When possible, the M&I curriculum includes observations of counterintuitive or puzzling real-world phenomena to motivate discussions of the application of fundamental principles to the real world. Examples include the observation that charged invisible tape is attracted to almost all objects (chapter 14), lighting a light bulb with a radio transmitter (chapter 23), and the counterintuitive behavior of pucks pulled from the side compared to pucks pulled from the center (chapter 8).

Research from the PER community

Qualitative reasoning: A large number of PER (physics education research) papers begin with the statement “students were found to have difficulty with ______”. In most cases, these papers report that students who were able to solve numeric or algebraic problems on a given topic, were unable to reason correctly when given qualitative problems on the same topic.[19,28, 29,30] This is a particular kind of lack of transfer -- the lack of transfer from a mathematical formula to a qualitative representation. The summary of these findings might be stated as follows: students who are not explicitly taught to reason qualitatively do not automatically gain this ability.

A clear lesson from this research is that if one of the instructional goals is qualitative understanding of physical principles, it is necessary to incorporate explicit instruction and explicit practice with this kind of reasoning. Studies by the developers and others (see below) indicate that this has been successful in some important areas.

Hierarchical knowledge organization: Eylon and Reif found that learners who organized their knowledge hierarchically were better able to recall long sequences of reasoning than were learners whose knowledge was organized as a single linear chain.[31] The M&I emphasis on a small number of fundamental principles is intended, in part, to facilitate hierarchical organization of students’ knowledge, and hence aid retrieval (by shortening the search path).

5.2 Formative research

The initial version of each volume of the textbook was based on a two-part analysis. This analysis focused on the intellectual structure of the curriculum, and on an initial task analysis of what knowledge students would need in order to engage in particular kinds of reasoning. Subsequent versions, of which there were many, were revised based on the detailed study of students’ written work on homework, quizzes, and exams (both solutions to quantitative problems and detailed, written, qualitative explanations involving both prose and diagrams), on discussions with students both in and out of class, and on observations of students’ difficulties in attacking large problems as they worked with other students in formal and informal group problem solving sessions. Information on students’ thinking and students’ difficulties collected in this way was used to revise and improve instruction, and did not result in formal published studies. Additionally, the development group did do more formal studies in specific areas, which are reported in this section.

Textbook format

The first version of the textbook was structured in workbook format, and required students to fill in steps in derivations, prose and diagrammatic explanations, and calculations, in empty boxes that appeared in line in the text. Full solutions were given at the end of each chapter. This format met with significant resistance from some instructors and some students, who argued that this format fragmented the text and interrupted chains of reasoning, and required too much writing. To study the utility of this format, toward the end of one semester, a study was made in which there was an unannounced check of students' workbooks, during a lab experiment to which they were required to bring their books. Because it was found that there was not a significant correlation between the number of workbook boxes completed by students and their scores on homework and exams, the workbook format was dropped and changed instead to the format discussed in section 5.1.

Another study, conducted by Matthew Kohlmyer,[32] explored the ways in which students used, or did not use, textbooks. Kohlmyer distributed a survey to students at a variety of institutions who had just completed a homework assignment. The survey asked how students had used the book in conjunction with the homework assignment. In addition, he interviewed a small number of students in detail. The study revealed a variety of patterns of textbook use. Different students used the book in different ways; some studied the text carefully before beginning the homework, others opened the book only if they encountered a homework problem they could not do. Some students read all of the text, while others only looked at worked out examples. Furthermore, individual students used the textbook in different ways at different times. For example, they read the text carefully when material was first presented, but later used it as a reference for looking up specific concepts or formulas. This data was convincing that the book needed to be made usable in a variety of modalities.

Students' perception of fundamentals

Do students studying the M&I curriculum in fact see and understand the power of fundamental principles in physics? One source of information is students' own reflections. Students were asked to write a paragraph to answer a question such as, "In your opinion, what was the most important concept in chapter 3?" Here are two examples of student reflections on the momentum section of the course, from students of quite different levels of sophistication:

> "In my opinion, the central idea in this chapter was to learn that atoms bonded to each other can be thought of as two balls connected to one another with a spring. Once we understood this concept, we could apply the models

> of springs from the macroscopic world to the atomic level, which gave us a general idea of how things work at the atomic level. Understanding that gave us the ability to predict vibrational frequencies of diatomic molecules and sound propagation in a solid. It is absolutely amazing how we can use very simple concepts and ideas such as momentum and spring motion to derive all kinds of stuff from it. I truly like that about this course."
>
> "Firstly, the momentum principle. Becuase you emphasized it every day to us. Also becse it can be applied to all kinds of motion: circular, ellipticle, and linear. It is definately better than learning all thoes kinestetic relations."

Of course one can object that these responses may not be representative. The key point however is that such statements were made at all (they were in fact quite common). Moreover, as improvements in the course were made it was observed that there was a significant rise in the fraction of students citing the momentum principle as the most important concept in the early part of the course, rather than citing peripheral concepts. (A more relevant comparison would require reflections from students in a traditional course, which are not available.)

A second measurement of students' view of fundamental principles was made in a problem-solving study, discussed in more detail below.

Impulse vs. work

McDermott and her colleagues have shown that even honors students in a traditional course have difficulty applying the concepts of work and impulse correctly when asked qualitative (non-numerical) questions involving these concepts.[21,22] These questions have been used periodically at Carnegie Mellon and NCSU in final exams as a calibration of students' ability to apply these concepts. The performance of honors level students at Carnegie Mellon, and physics majors at NC State, was significantly better than that of high scoring honors students at the University of Washington. Currently the performance of average engineering students at NCSU is about the same as that of students in the traditional course at UW, indicating that it is necessary to further refine instruction for this population.[33]

Student attitudes toward physics

The University of Colorado PER group has developed an instrument, CLASS,[34] which attempts to assess student attitudes toward science.[35] As with similar instruments such as MPEX,[36] it is typical for CLASS pretest and posttest scores to show a worsening of student attitudes toward physics as a result of taking a physics course. However, in a couple of particularly well-taught physics courses at the University of

Colorado the CLASS scores did not change from before to after the course, which was considered something of a victory.[37] A CLASS pretest/posttest comparison in Modern Mechanics at NCSU in Fall 2005 also showed no change. CLASS was administered anonymously in one lecture section. The average posttest result for the 60 students present for the posttest was the same as the average of the highest 60 pretest scores, so one can say that the CLASS score for those who took the posttest at a minimum did not go down and may even have gone up.

Computation

A study by Matthew Kohlmyer, at NC State, focused on the difficulties students had in attempting to apply fundamental principles in computational mechanics problems such as modeling a planetary orbit.[38] An analysis of students' difficulties led to two successive revisions of the initial instruction on programming and on 3D vectors. Recent results using the revised instruction suggest that students are now beginning to feel comfortable writing programs to solve problems. A significant issue is that student computation has rarely been a part of the introductory physics course, so there is little prior research or practice to guide how best to teach this important component of contemporary physics**.**

5.3 Summative research: Assessment of student learning in M&I compared to traditional courses

BEMA

Because *Electric & Magnetic Interactions* (volume II of *Matter & Interactions)* was developed first, there have been more formal assessments of it than of *Modern Mechanics* (volume I of M&I). Various studies have compared the performance of students who have completed the revised E&M sequence with the performance of students who have taken a traditional introductory E&M course. Of necessity, these comparisons have been restricted to standard topics covered in both courses and do not measure how well students have learned the material that is unique to the new sequence.

One assessment was a longitudinal study of what students learn and retain in the introductory E&M course. The basic finding reported in Chabay and Sherwood[39] was that on a test of basic E&M concepts (BEMA, Brief E&M Assessment) administered at Carnegie Mellon, students in the M&I version of E&M scored one letter grade better than did comparable students in a traditional course. That is, M&I "B" students scored as well as traditional "A" students, etc. In educational comparisons this is a big effect. This effect persisted for 5 semesters after completing the course. There were no significant differences in the two groups with respect to grade point average, SAT scores, calculus grades, etc., and the pedagogical approach in both kinds of course was similar.

For the study at Carnegie Mellon, email from a person not connected with physics was sent to all students, freshmen through seniors, who had taken some form of introductory E&M. The email invited the students to take a test for pay dealing with an introductory course they had taken. The students who came to the test did not know what subject was being tested, so they didn't have an opportunity to review. There were 116 students who had taken the traditional E&M course and 73 who had taken the M&I version, spread across 5 semesters and thus forming a slice at one time, which can be considered equivalent to a longitudinal study. BEMA was specifically designed to include only topics common to both traditional and M&I treatments of E&M and does not test topics that are covered only in M&I, such as the surface charge model of circuits.

After verifying the reliability of BEMA as an assessment instrument (Ding et. al. 2004, 2006),[40,41] this measurement was repeated at North Carolina State University, with students recruited from traditional and M&I sections of the second semester introductory calculus-based physics course. Again, students in M&I scored significantly higher than students in the traditional course; they showed about twice the gain from the pretest level, which is a very large effect. The two groups of students were otherwise indistinguishable (their distribution of GPAs and final grades in the physics and calculus courses were the same). There was no significant difference among the four traditional lecture sections (taught by four different faculty), nor among the four M&I lecture sections (taught by four different faculty).

It is interesting that BEMA pretest scores are similar at different institutions, apparently because few students have much previous experience with the subject and the technical nature of the concepts and vocabulary precludes answering correctly based solely on common knowledge. This is quite different from the situation with the Force Concept Inventory (FCI) for which the pretest scores vary a great deal among institutions. Posttest scores on BEMA depend on curriculum (with M&I students doing better than traditional students) and on institution (students with stronger backgrounds get further in their study of E&M). In contrast, FCI normalized gains, computed as the fraction of possible gain, depend mainly on pedagogy (with students in active learning classes doing better than students in classes using traditional pedagogy) and do not depend strongly on institution.[18]

To obtain a copy of BEMA, go to http://www.per-central.org and search for BEMA, then click on Details, then on "View attached documents." Contact the authors for the password required to open the zip file, which includes BEMA and a spreadsheet for analyzing student data. It is necessary to protect assessment instruments such as BEMA because a large effort is required to create and validate such a test, and easy access would compromise its utility.

RC and DC circuits

A study by Thacker, Ganiel, and Boys showed that students in the M&I version of the E&M curriculum approached difficult, novel capacitor problems significantly better than students in a traditional curriculum.[42] Moreover, the M&I students started from fundamental physics principles, with a deep sense of mechanism, while the other students just manipulated formulas with little sense of the physics.

In the study by Engelhardt and Beichner, [43] see the section on “Instructional method” on p. 105 for a comparison between M&I and traditional instruction dealing with simple circuits.

Complex problem solving

A study by Sherwood and Chabay dealt with complex problem solving.[44] Three big problems on a final exam were identical in two courses serving indistinguishable populations of students–one traditional, the other using M&I. The number of students who got each problem fully correct was counted in each course, the criterion of correctness (other than trivial arithmetic mistakes) being one that could be applied with no ambiguity. For two problems there was no significant difference. For the third problem, the most complex (consisting of many steps), the performance of the M&I students was four times higher than that of the students in the traditional curriculum (30% correct vs. 7.5%).

Approach to difficult mechanics problems

In mechanics, a detailed protocol study done by Matthew Kohlmyer at Carnegie Mellon (necessarily involving a small number of students, 6 from a traditional course and 5 from M&I) compared the approaches of students in the traditional course and M&I to very difficult, novel problems.[45,46,47] The problems were not solvable analytically with the mathematical tools available to college freshmen. For example, one problem specified the initial position of a spacecraft in the neighborhood of the Earth, with both radial and tangential components of the initial velocity. The spacecraft rocket acted for 10 minutes with known thrust. What were the position and velocity 15 hours later? The only feasible solution path requires carrying out a numerical integration on a computer.

Although the original intent of the study was merely to see whether students took an iterative approach to the solution, a striking difference in approach emerged in the analysis of the protocols. Every student in the M&I version of the course started his or her attack on each problem by invoking a fundamental principle (the momentum principle or the energy principle; the students had not yet encountered angular momentum in the course). Even though not all of the M&I students were able to carry out the solution without error, all of them recognized that these principles could be applied to these problems and attempted to start by applying them. In contrast, most students in the traditional course attempted to map the problems onto problems whose solution was known to them (for example, trying to reduce a problem involving an elliptical orbit, with a briefly applied rocket force, to a situation of circular motion at constant speed). One student, recognizing that he had never seen such a problem before, simply gave up.

One traditional student flipped through the book and specifically said that he was looking for “equations for motion of satellites.” Another said he was looking in the book for “motion of satellites” to see if he could find a “complicated problem like the one I have.” In general, the traditional students made far more use of the book than M&I students, particularly in flipping through the book, searching for some help on how to proceed.

6. Implementation: An example of course structure and format

The *Matter & Interactions* curriculum is currently in use with some or all engineering and science students at a variety of institutions, including large state engineering and science universities (NCSU, Purdue, Georgia Tech), small private universities (Carnegie Mellon, High Point, Drexel), four-year liberal arts colleges (Carleton, St. Olaf), and two-year community colleges (Catawba Valley, NC). Two reviews of the textbook have been published.[48,49]

In physics education research dealing with improving pedagogy in the context of the traditional introductory calculus-based course, many of the findings are very specific to the traditional curriculum and are of limited usefulness for guiding the continued improvement of the teaching of the *Matter & Interactions* curriculum. However, much research has dealt with general issues, especially the importance of active learning on the part of the student, and how to organize instruction in order to maximize active learning. These general results have contributed to the teaching of the M&I curriculum.

Because M&I is first and foremost about changing the content and emphases, not about pedagogy, different institutions will implement the curriculum in different ways, depending on personal taste, local constraints and opportunities, available staff, etc. Nevertheless, it is useful to have a detailed example of a specific implementation as a proof of concept and a possible roadmap to follow if one decides to try out this curriculum.

It is important to bear in mind that such large courses require extensive formal structure that is not needed in small-enrollment classes.

Every week there are three 50-minute lectures and a 110-minute lab. Most of the faculty involved give interactive lectures. Students use electronic “clickers” to respond to questions during the lecture, and they are frequently asked to do small calculations during lecture. There are 70 to 100 students in the lecture. In some semesters a brief paper quiz has been given once a week in lecture, to encourage students to keep current with the material and to give them practice in writing out solutions. Grading of the weekly quizzes is done by undergraduate teaching assistants.

Lab activities are integrated with other components of the course (textbook, lectures, homework). The lab might better be called a studio, as it involves a variety of activities: experiments, writing computer programs to model physical system or fields, and small-group problem solving on small whiteboards. In any particular lab day students typically do two of these three activities. There are 24 students in the lab room, aided by a physics graduate student teaching assistant (TA) and an undergraduate teaching assistant (UTA). The UTA recently took the M&I course and did well in it, and also showed good personal skills in the lab when working with partners. The TA’s know more physics, but the UTA’s know more about the course, having recently experienced it as students.

6.1 Experiments

It is the case that curricula and textbooks are usually national in character but laboratory experiments are typically local, building on particular apparatus and settings. Nevertheless, for completeness it is useful to describe the NCSU implementation of laboratory aspects of the course.

The experiments in the weekly studios are minilabs that take about an hour to do, including extensive analysis, and students turn in a worksheet. There are many possible goals for experimental labs. A choice has been made to emphasize vivifying the theory and seeing phenomena in the real world, with careful analysis of the observations. Given limited time, and the priorities of the course, it has been necessary to forego serious engagement with most aspects of error analysis.

In the case of E&M, a desktop experiment kit was developed that is distributed by PASCO (item EM- 8675). It contains in a small box sufficient equipment to permit doing significant experiments with electrostatics, circuits, and magnetism (but not

Faraday's law, which requires more elaborate apparatus). In some settings students own the kits and bring them to class to do just-in-time experiments, even in lecture. At NCSU kits are available in the lab, together with more conventional equipment such as multimeters. Details of the contents of the E&M experiment kit are available at http://www4.ncsu.edu/~rwchabay/mi. The kit components were deliberately chosen to be simple, in order to bring out the essence of the phenomena uncluttered by complex apparatus where possible. For example, invisible tape is used to investigate some deep issues in electrostatics.

6.2 Computation

For the computational modeling component of the course, students start each program in the lab working in pairs at a computer. The TA and UTA circulate and ask and answer questions about the task. Often students may finish the program during the lab, but if not, they can finish it outside of class since they can install VPython on their own computer at no cost (vpython.org) or use it in a public cluster. They turn in the program to the WebAssign homework system by uploading the file. The fact that students start the program in class diminishes the problem of simply copying someone's file from last semester; the situation is somewhat like experiments, which are typically repeated one semester after another. Also, the questions asked in the WebAssign computer homework system about the program change from semester to semester, as do some of the specific conditions specified, such as initial conditions for a binary star orbit.

6.3 Problem solving

The third type of activity in the lab is the working out of big, complex problems in groups of two or three students clustered around a small whiteboard (24 by 19 inches, 60 cm by 48 cm, cut from inexpensive whiteboard available at places like Home Depot or Lowe's). The students have a blunt marker that forces them to write large enough for everyone in the group, and the instructors, to be able to see the work easily. The intent is to offer coached practice in how to carry out full analyses starting from fundamental physics principles, something that students need a lot of help with because it is so different from their prior experience with plugging numbers into special-case formulas.

6.4 TA training

There is a one-hour course meeting every week with the TA's and UTA's to discuss in detail what will happen in lab the following week. There is just-in-time teaching of some physics that is unfamiliar to the TA's, such as work and energy for deformable systems, or the surface charge model of circuits. The TA's and UTA's receive carefully planned scripts of what to do in class, including in particular questions to ask of students when they have completed an activity. When a group finishes an activity, they get checked off by an instructor, and completion of these checkpoints constitutes part of the lab grade, the rest coming from the grading of lab worksheets and programs.

Of particular importance are the questions posed by instructors (and in WebAssign) about the computer programs. Initially it was common for students not to see much of a connection between the writing of a program and the rest of the activities in the course, and some students approached the computational aspect of the course as something to be done by rote, with little impact on learning. By asking students the right kind of probing questions most students are making the desired connections. It is particularly gratifying when students spontaneously comment that the Rutherford scattering program is essentially the same as their binary star program, despite the difference in scale of 25 orders of magnitude!

6.5 Other formats

The rather elaborate course format described above is typical of very large courses at big research-oriented universities. Courses involving small numbers of students with lots of faculty-student contact need far less formal infrastructure in order to run well.

Having three lectures and one two-hour lab/studio every week is not ideal. It would be much better to have in addition a one-hour "recitation" as is true in many such courses at other universities. The additional hour would be used for more whiteboard problem solving, because the students could benefit from more practice on big problems than can be provided in the current class schedule.

An alternative course structure at NCSU involves the SCALE-UP full studio environment (see article in this volume, and http://www.ncsu.edu/per/scaleup.html), within which Robert Beichner and John Risley have been teaching *Matter & Interactions*, both mechanics and E&M.

6.6 Grading of homework and tests

When M&I is delivered to very large classes, the computer homework system WebAssign (webassign.net) can be an important component in the course. Initially, there was skepticism that the kinds of homework problems that are integral to the M&I approach could be handled adequately by a computer homework system. However, by careful exploitation of the diverse capabilities of the WebAssign system, it was possible to create WebAssign versions of problems that support the curriculum well. While necessarily inferior to the best hand grading of written solutions theoretically possible, in the real world of large-enrollment courses this approach has proven to be not only feasible but arguably of higher quality than would be realistically achievable otherwise.

The textbook version of a homework problem on symmetrical fission was shown in figure 2. Figure 8 shows the WebAssign version of that problem. The parent nucleus is chosen at random from among a sizable number of fissionable nuclei, so that different students have different reactions to analyze.

> For some isotopes of some very heavy nuclei, including nuclei of thorium, uranium, and plutonium, the nucleus will fission (split apart) when it absorbs a slow-moving neutron. Plutonium-239, with 94 protons and 145 neutrons, can fission when it absorbs a neutron and becomes Plutonium-240. The two fission fragments can be almost any two nuclei whose charges Q_1 and Q_2 add up to 94e (where e is the charge on a proton, $e = 1.6\times10^{-19}$ coulomb), and whose nucleons add up to 240 protons and neutrons (Pu-240, formed from Pu-239 plus a neutron). One of the possible fission modes involves nearly equal fragments, silver nuclei (Ag) each with electric charge $Q_1 = Q_2 = 47e$. The rest masses of the two silver nuclei add up to less than the rest mass of the original nucleus. (In addition to the two main fission fragments there are typically one or more free neutrons in the final state; in your analysis make the simplifying assumption that there are no free neutrons, just two silver nuclei.)
>
> The rest mass of the Pu-240 nucleus (formed from Pu-239 plus a neutron) is 240.002 u (unified atomic mass units), and the rest mass of each of the two Ag-120 nuclei is 119.893 u, where 1 u = 1.66×10^{-27} kg (approximately the mass of one nucleon). In your calculations, keep at least 6 significant figures, because the calculations involve subtracting large numbers from each other, leaving a small difference. There are three states you should consider in your analysis:
>
> 1) The initial state of the Pu-240 nucleus, before it fissions.
>
> 2) The state just after fission, when the two silver nuclei are close together, and momentarily at rest.
>
> 3) The state when the silver nuclei are very far away from each other, traveling at high speed.
>
> (a) Calculate the final speed v, when the silver nuclei have moved very far apart due to their mutual electric repulsion. Keep at least 6 significant figures

in your calculations. In your analysis it is all right to use the nonrelativistic formulas, but you then must check that the calculated v is indeed small compared to c. (The large kinetic energies of these silver nuclei are eventually dissipated into thermal energy of the surrounding material. In a nuclear reactor this hot material boils water and drives an electric generator.)

v = ☐ m/s

Is the speed of each silver nucleus small enough that $(1/2)mv^2$ or $p^2/(2m)$ is an adequate approximation for the kinetic energy of one of the silver nuclei?

☐ no

☐ yes

☐ not enough information to tell

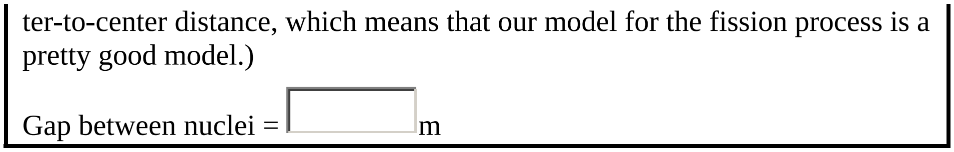
(b) Using energy considerations, calculate the distance between centers of the silver nuclei just after fission, when they are momentarily at rest. Keep at least 6 significant figures in your calculations.

Distance between centers = ☐ m

(c) A proton or neutron has a radius r of roughly 1×10^{-15} m, and a nucleus is a tightly packed collection of nucleons. Therefore the volume of the nucleus, $(4/3)\pi R^3$, is approximately equal to the volume of one nucleon, $(4/3)\pi r^3$, times the number N of nucleons in the nucleus: $(4/3)\pi R^3 = N(4/3)\pi r^3$. So the radius R of a nucleus is about $N^{1/3}$ times the radius r of one nucleon. More precisely, experiments show that the radius of a nucleus containing N nucleons is $(1.3\times10^{-15}\text{ m})\ N^{1/3}$. What is the radius of a silver nucleus?

R = ☐ m

(d) On paper, make a careful scale drawing of the two silver nuclei in part (b), just after fission, and label the drawing with the distances that you calculated in parts (b) and (c). If the two silver nuclei are nearly touching, this would be consistent with our model of fission, in which the Pu-240 nucleus fissions into two pieces that are initially nearly at rest. How big is the gap between the surfaces of the two nuclei? (If you have done the calculations correctly, you will indeed find that the gap is a rather small fraction of the cen-

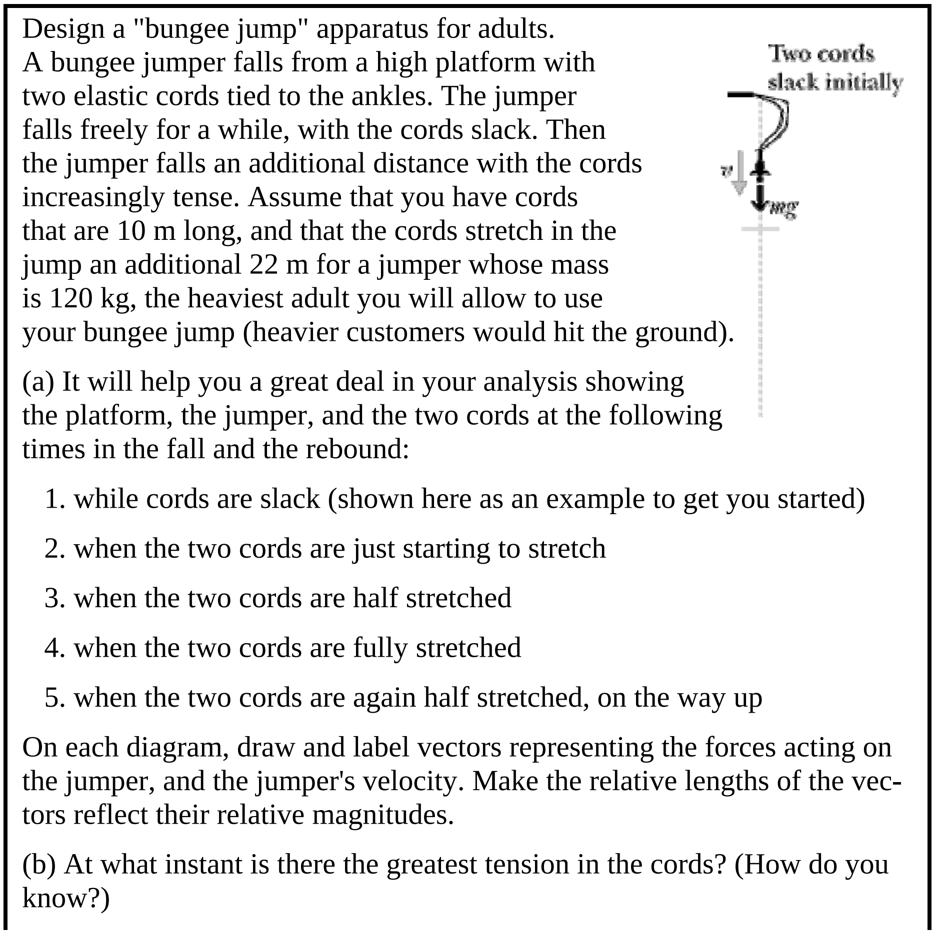


ter-to-center distance, which means that our model for the fission process is a pretty good model.)

Gap between nuclei = ☐ m

Fig. 8: The WebAssign version of the homework problem on symmetrical fission (see Fig. 2). The parent nucleus is chosen at random from among a sizable number of fissionable nuclei, so that different students have different reactions to analyze.

The WebAssign version of a design problem from the textbook asks about the solution method as well as about the final results. This is shown in figure 9.



Design a "bungee jump" apparatus for adults.
A bungee jumper falls from a high platform with two elastic cords tied to the ankles. The jumper falls freely for a while, with the cords slack. Then the jumper falls an additional distance with the cords increasingly tense. Assume that you have cords that are 10 m long, and that the cords stretch in the jump an additional 22 m for a jumper whose mass is 120 kg, the heaviest adult you will allow to use your bungee jump (heavier customers would hit the ground).

(a) It will help you a great deal in your analysis showing the platform, the jumper, and the two cords at the following times in the fall and the rebound:

1. while cords are slack (shown here as an example to get you started)
2. when the two cords are just starting to stretch
3. when the two cords are half stretched
4. when the two cords are fully stretched
5. when the two cords are again half stretched, on the way up

On each diagram, draw and label vectors representing the forces acting on the jumper, and the jumper's velocity. Make the relative lengths of the vectors reflect their relative magnitudes.

(b) At what instant is there the greatest tension in the cords? (How do you know?)

☐ At the top, when the person has fallen 0 m.

☐ When the person has fallen between 0 m and 10 m.

☐ When the person has fallen between 10 m and the bottom.

☐ When the person has fallen 10 m.

☐ At the bottom, when the person has fallen 32 m.

(c) What is the jumper's speed at this instant, when the tension is greatest in the cords?

v = ☐ m/s

(d) Is the jumper's momentum changing at this instant or not? (That is, is dp_y/dt nonzero or zero?)

☐ No, the jumper's momentum is not changing.

☐ Yes, the jumper's momentum is changing.

(e) Which of the following statements is a valid basis for answering part (d) correctly?

☐ After a very short time the momentum will be upward (and nonzero).

☐ If the momentum weren't changing, the momentum would remain zero forever.

☐ A very short time ago the momentum was downward (and nonzero).

☐ Since the momentum is zero, the momentum isn't changing.

☐ Since the net force must be zero when the momentum is zero, and since dp_y/dt is equal to the net force, dp_y/dt must be zero.

Check to make sure that the magnitudes of the velocity and force vectors shown in your diagram number 4 are consistent with your analysis of parts (c), (d), and (e).

(f) Focus on this instant of greatest tension and, starting from a fundamental principle, determine the spring stiffness k_s for each of the two cords.

k_s = ☐ N/m

(g) What is the maximum tension that **each one** of the two cords must support without breaking? (This tells you what kind of cords you need to buy.)

F_T = ☐ N

(h) What is the maximum acceleration $|a_y| = |dv_y/dt|$ (in "g's") that the jumper experiences? (Note that $|dp_y/dt| = m|dv_y/dt|$ if v is small compared to c.)

$|a_y|$ = ☐ g's (acceleration in m/s^2 divided by 9.8 m/s^2)

(i) What is the direction of this maximum acceleration?

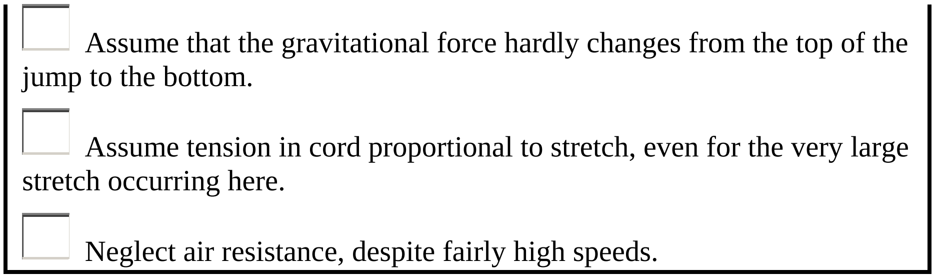
☐ no direction, since the acceleration is zero

☐ upward

☐ downward

(j) What approximations or simplifying assumptions did you have to make in your analysis that might not be adequately valid? (Don't check any approximations or simplifying assumptions that in fact have negligible effects on your numerical results.)

☐ Assume the speeds are very small compared to the speed of light.



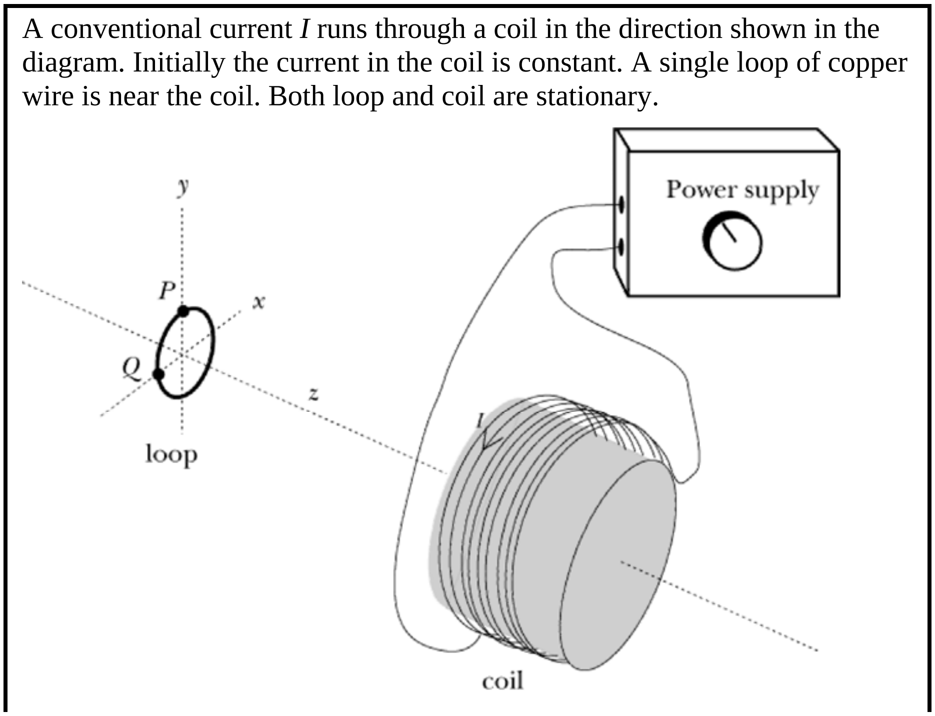
☐ Assume that the gravitational force hardly changes from the top of the jump to the bottom.

☐ Assume tension in cord proportional to stretch, even for the very large stretch occurring here.

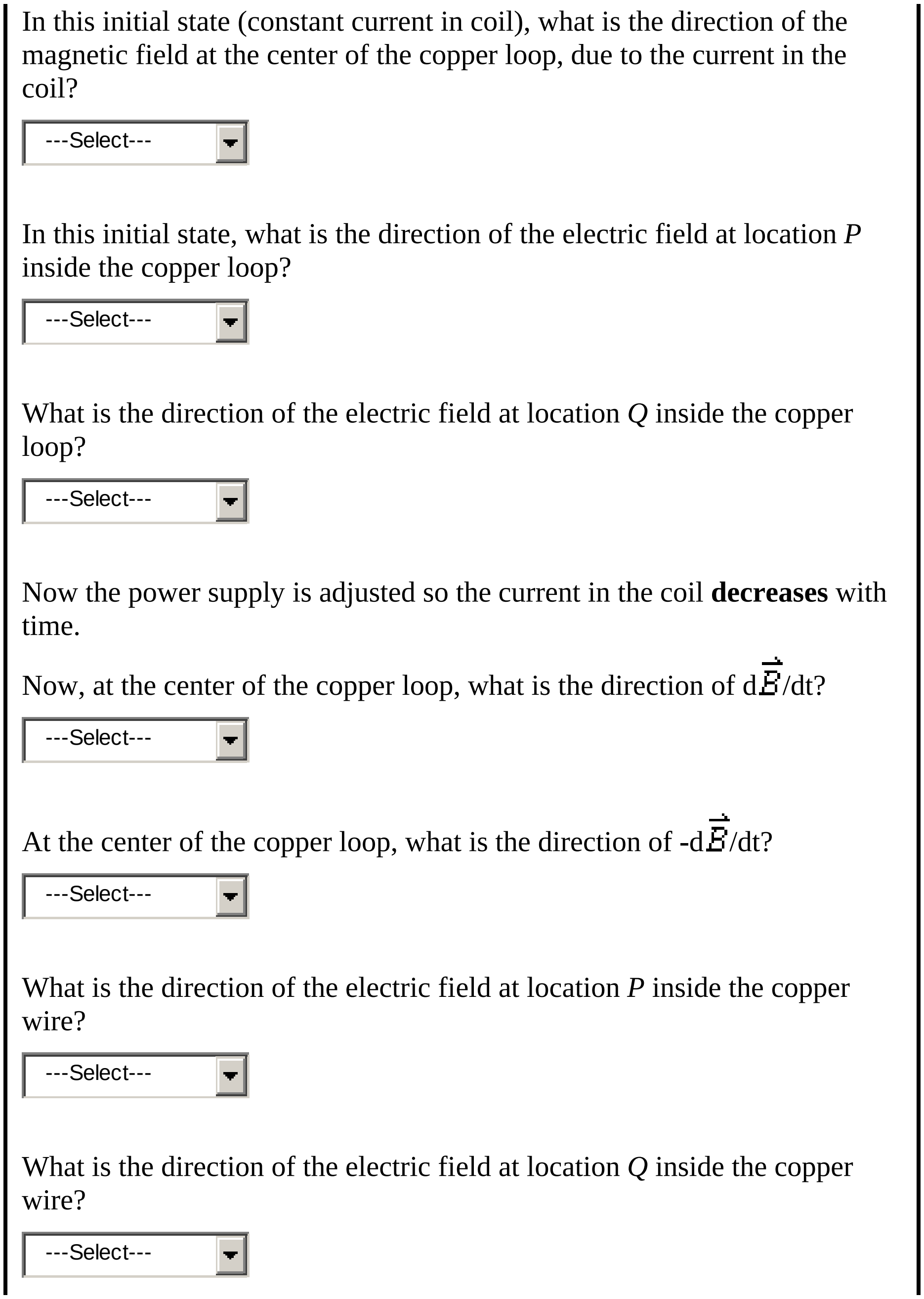
☐ Neglect air resistance, despite fairly high speeds.

Fig. 9: This WebAssign version of a design problem from the textbook asks about the solution method as well as about the final results.

The next two WebAssign problems are a connected pair. The first problem (figure 10) deals with qualitative aspects and provides lots of scaffolding. The second problem asks students to work more independently on a similar problem (figure 11). Numerical values in the problem are chosen randomly and are different for different students.



A conventional current *I* runs through a coil in the direction shown in the diagram. Initially the current in the coil is constant. A single loop of copper wire is near the coil. Both loop and coil are stationary.



In this initial state (constant current in coil), what is the direction of the magnetic field at the center of the copper loop, due to the current in the coil?

In this initial state, what is the direction of the electric field at location *P* inside the copper loop?

What is the direction of the electric field at location *Q* inside the copper loop?

Now the power supply is adjusted so the current in the coil **decreases** with time.

Now, at the center of the copper loop, what is the direction of $d\vec{B}/dt$?

At the center of the copper loop, what is the direction of $-d\vec{B}/dt$?

What is the direction of the electric field at location *P* inside the copper wire?

What is the direction of the electric field at location *Q* inside the copper wire?

Is the magnitude of the magnetic flux inside the copper loop changing at this moment?

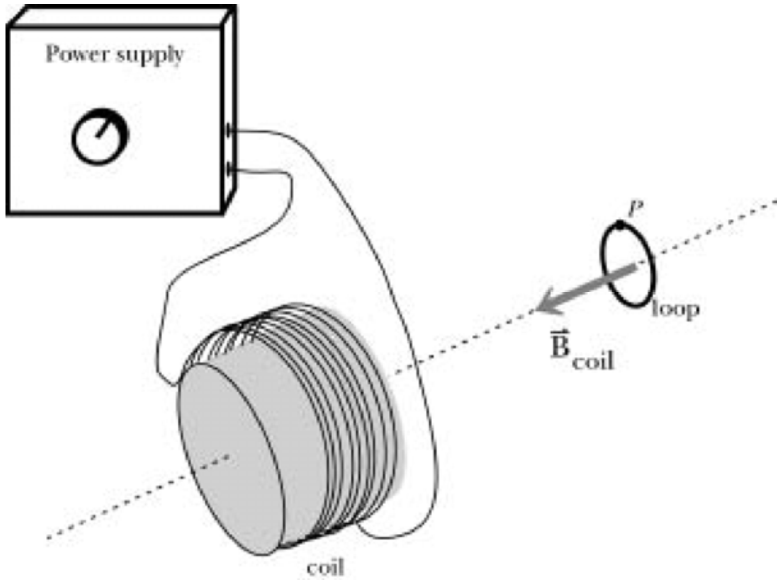
☐ The magnitude of the magnetic flux inside the loop is decreasing.

☐ The magnitude of the magnetic flux inside the loop is increasing.

☐ The magnetic flux inside the loop is constant.

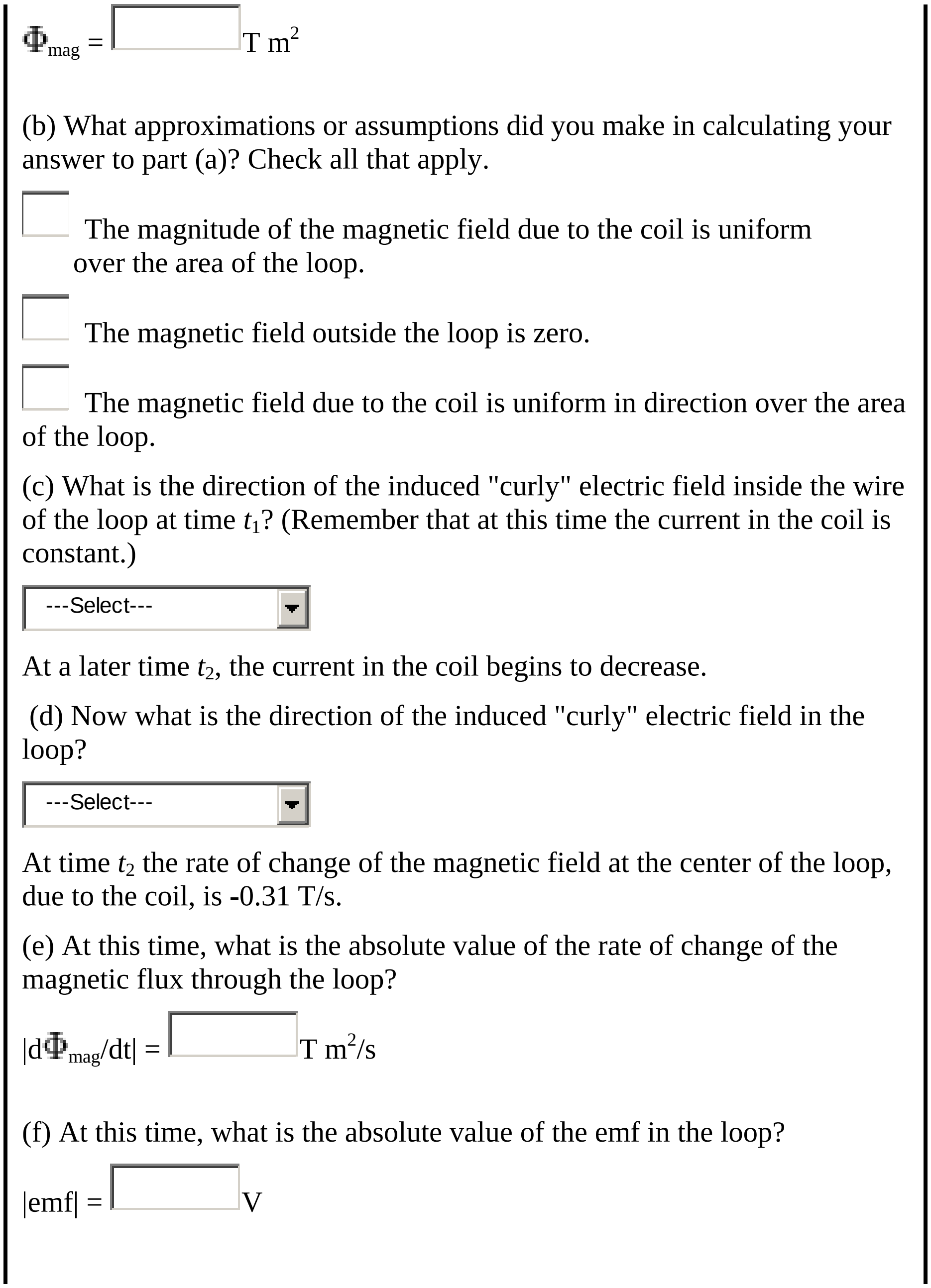
Fig. 10: This WebAssign problem and that shown in Fig. 11 are a connected pair. This first problem deals with qualitative aspects and provides lots of scaffolding. The second problem asks students to work more independently on a similar problem.

A coil of wire is connected to a power supply, and a current runs in the coil. A single loop of wire is located near the coil, with its axis on the same line as the axis of the coil. The radius of the loop is 2 cm.



At time t_1 the magnetic field at the center of the loop, due to the coil, is 0.7 T, in the direction shown in the diagram; the current in the coil is constant.

(a) What is the absolute value of the magnetic flux through the loop at time t_1?



Φ_{mag} = T m^2

(b) What approximations or assumptions did you make in calculating your answer to part (a)? Check all that apply.

☐ The magnitude of the magnetic field due to the coil is uniform over the area of the loop.

☐ The magnetic field outside the loop is zero.

☐ The magnetic field due to the coil is uniform in direction over the area of the loop.

(c) What is the direction of the induced "curly" electric field inside the wire of the loop at time t_1? (Remember that at this time the current in the coil is constant.)

At a later time t_2, the current in the coil begins to decrease.

(d) Now what is the direction of the induced "curly" electric field in the loop?

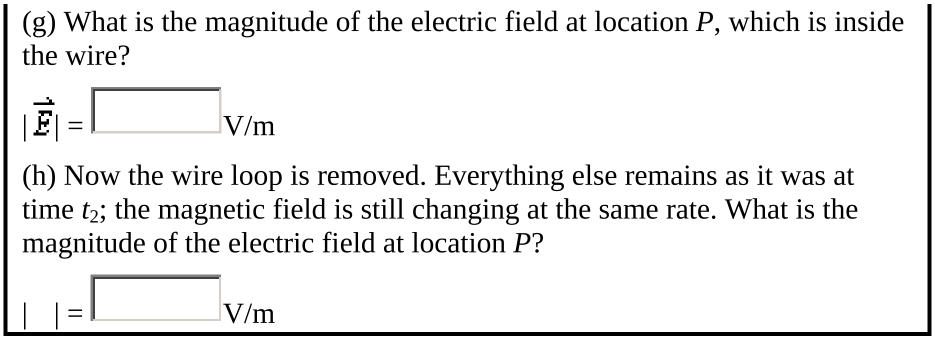
At time t_2 the rate of change of the magnetic field at the center of the loop, due to the coil, is -0.31 T/s.

(e) At this time, what is the absolute value of the rate of change of the magnetic flux through the loop?

$|d\Phi_{mag}/dt|$ = T m^2/s

(f) At this time, what is the absolute value of the emf in the loop?

|emf| = V



(g) What is the magnitude of the electric field at location *P*, which is inside the wire?

$|\vec{E}|$ = ☐ V/m

(h) Now the wire loop is removed. Everything else remains as it was at time t_2; the magnetic field is still changing at the same rate. What is the magnitude of the electric field at location *P*?

| | = ☐ V/m

Fig. 11: Here is the second, less scaffolded member of the pair of problems (see Fig. 10). Numerical values in the problem are chosen randomly and are different for different students.

The textbook contains many exercises at the end of each section of a chapter, and an adequate number of large problems at the end of the chapter, but is currently somewhat lacking in medium-size problems for some topics. In developing the suite of WebAssign exercises and problems, additional medium-sized problems were created, and these will be incorporated into a future edition of the textbook. A number of institutions that are using M&I have elected to use the WebAssign activities in their courses.

Grading of the lab worksheets by the TA's is quite quick and doesn't require much time. The grading of computer programs is parceled out to the TA's and UTA's, and this too is quite quick. They download from WebAssign the programs for the students they're assigned to grade, then run a "grading program" (also written in Python) which one after another runs each student's program and displays the program code. The main criterion for correctness is whether the 3D graphics display looks correct. Usually all the grader needs to do is to enter into WebAssign a brief comment and score (e.g., -1 for missing force vector). This goes very quickly.

Three paper problem-solving tests are given during the semester plus a comprehensive paper final exam, and these are all graded by lecturers, TA's, and UTA's working in one room together in teams devoted to a single problem, with lots of communication within the group about the grading of that problem. The total number of lecturers, graduate student TA's, and undergraduate UTA's is such that there are about 30 students in the course per staff member. As a result, grading a test takes about three- and-a-half hours in the evening after the test, and the final exam takes about six hours.

It has seemed important to give paper tests in order to be able to challenge students with serious problems yet be able to give abundant partial credit. In particular, a simple arithmetic mistake is just a one-point deduction. If one were to grade essentially only for the correct answer, one would have to ask either trivial questions and/or break problems down into tiny steps. Since tests largely determine student views of what is important to learn, and a major goal is to have students learn to attack large problems, there seems to be no alternative to giving (and grading) paper tests. As was mentioned earlier, weekly quizzes are graded by undergraduate UTA's.

Note that UTA's are a wonderful resource in large courses because they represent the only resource that scales with the course enrollment, being recruited from the ranks of those who took the course. They are currently paid $10 per hour, which they see as acceptable, and they feel that they learn a lot from the experience.

6.7 Prerequisites

Modern Mechanics has the usual corequisite of first-semester calculus (at some institutions including NCSU calculus is a prerequisite). Reliance on formal calculus is avoided at first, and in some cases (such as energy, which comes rather early) antiderivatives are used rather than integrals to accommodate students who haven't yet had formal integration. The early emphasis on finite differences and numerical integration provides another important view on the fundamental ideas of calculus.

It was initially assumed that it would be important for a student to have had high school physics before starting M&I. Indeed, one of the motivations for developing the curriculum was to avoid simply repeating the high school physics course. However, it has been found experimentally in a situation where many of the engineering students did not have any prior physics that M&I is accessible to these students, and there is no correlation between prior physics study and scores on tests. Perhaps what is happening is that M&I starts in a rather different place (momentum) and goes in a very different direction (emphasis on fundamental principles), with the result that it doesn't matter very much whether the student has previously studied physics in a traditional way, though it may be that those students without prior physics have to work somewhat harder. Occasionally students who received a 5 on an AP physics test elect to take M&I anyway, and they are not bored.

6.8 Different student populations

As mentioned earlier, *Matter & Interactions* is used at diverse kinds of institutions. M&I has been used in an honors course at Carnegie Mellon with very well prepared students drawn from a national pool, and in a regular course at NCSU with students drawn almost exclusively from within the state, some of whom are quite poorly prepared and may never have studied physics before. M&I works well in both environments, but it was possible to go significantly farther and deeper at Carnegie Mellon than is possible at NCSU, where it is necessary to omit some interesting topics and assign less challenging homework problems. Also, the goal of teaching students to model unfamiliar phenomena, including making simplifying assumptions, approximations, estimates, etc. was rather well achieved with the high performing group but as yet not something the less well prepared students are able to do well.

When we moved from Carnegie Mellon to NCSU in 2002, it was found necessary to make important revisions to the textbook and to the pedagogical structure of the course, including the development of a large suite of WebAssign versions of homework exercises and problems, in order for M&I to work well in a huge course at NCSU (about 1600 students per semester). The key point is that it does now work well, though of course there is continuing work to make further improvements.

7. Instructor resources

There is a very extensive set of instructor resources to support the teaching of *Matter & Interactions*. These resources are available through a public web site accessible to everyone, and a private collaborative web site maintained by instructors who are using *Matter & Interactions,* with materials for adopters and potential adopters.

7.1 Instructor resources

Public web site (http://www4.ncsu.edu/~rwchabay/mi):

- PowerPoint presentations and articles about the curriculum
- Lecture-demonstration software for mechanics and E&M
- A video of an unusual lecture demonstration dealing with multiparticle systems
- How to order textbooks and the PASCO E&M experiment kit
- How to join the Matter & Interactions online discussion group
- How to register for access to the private web site

Private web site maintained by M&I instructors for adopters and potential adopters:

- Daily log of lecture and lab activities; enhanced lecture notes
- Example of course web site as seen by students, including calendar, handouts, etc.
- Detailed catalog of WebAssign homework assignments

- Clicker questions for making lectures interactive
- Problem solutions including solutions to VPython program assignments
- Tools that simplify grading VPython programs
- Sample quizzes, tests, and final exams
- Additional materials contributed by various Matter & Interactions instructors

Three American Journal of Physics papers previously mentioned are particularly useful for a detailed overview of the curriculum (refs. 2, 3, and 4).

In the past there have been half-day workshops at meetings of the American Association of Physics Teachers and of the American Physical Society. There are plans to offer in-depth workshops lasting several days in the summer, separate from physics conferences.

7.2 Video lectures and distance learning

There exist videos of all the lectures, in the form of highly compressed Real Player files (one semester's worth of lectures fits on 4 CD's or one DVD). These have proven useful to lecturers for getting ideas and for judging the pacing of topics. Instructions for obtaining these video lectures may be found on the private web site.

A special interactive version of these video lectures has been used to offer a distance education version of *Matter & Interactions* for in-service high school physics teachers. The intent is not to train teachers to teach this college course in high school, but rather to broaden and deepen their culture in physics through a fresh, contemporary approach. In the interactive version of the video lectures, lectures are presented as segments that end with a clicker question that was posed to the class when the lecture was captured, and a simulated clicker appears on the computer screen. After making a choice, the next segment is presented and the learner sees a histogram of responses from students in the original class, with discussion of these responses. As a result, much of the interactivity of the original lecture is preserved in the distance learning course.

Reactions of high school teachers who have taken this course have been highly enthusiastic. The material is at a level close to that of their own teaching, yet much of the content is novel, as is the emphasis on the reductionist nature of physics. Here are quotes from two teachers about the course:

> "Is it worth the time and effort? For me, without a doubt, even though I have a Ph.D. in a related area. I learned an incredible amount including some things I never did understand properly when I took physics as an undergrad, or when, unfortunately, I try to teach it to my students!"
>
> "Learning physics based on a fundamental set of principles makes it intuitively appealing. Rather than fumbling through flip charts of formulas, M&I asks students to make connections between a few formulas and the entire first semester curriculum. You become rather attached to some of the principles by the end of the course."

8. Possible difficulties in implementation

The most crucial requirement for success in running a course using the *Matter & Interactions* curriculum is the availability of recitation or lab time devoted to having students practice attacking large novel problems with coaching available by TA's and/or UTA's. It is likely that a course consisting solely of lectures and experiments, without significant amounts of time every week devoted to practice in problem solving, will not work satisfactorily. Students need help and support and practice in working through complex multistep problems, and it is only through wrestling with complex, novel problems that students can come to appreciate the value of starting analyses from fundamental principles.

At some institutions there are no recitations, or no labs, or no required labs. It is doubtful whether the M&I curriculum is viable at such institutions. However, it may well be that there are ways to use this curriculum even in such settings, though presumably the results will be less satisfactory than desired (of course this is likely to be the case with a traditional curriculum in such settings, too).

An important issue is that in many institutions students come to the introductory calculus-based physics course with little prior experience with long chains of reasoning. Often their prior experience involved problems involving at most one step in reasoning. One must take special precautions to provide appropriate support and gently contribute to their intellectual development so that eventually they can attack large novel problems. A key element is adequate scaffolding initially, which is progressively removed as the students become more capable of independent thought.

A concern that is frequently raised has to do with the feasibility and advisability of introducing computer programming into the introductory course, especially if students and instructors are unfamiliar with programming. It should be emphasized that computing is not the most important component of the curriculum, and it should not and need not loom larger than other components, yet it is important. In the last few years there have been developed greatly improved methods for introducing students to computational physics, and for helping them make the desired connections between numerical and analytical approaches, and these materials are available to instructors. As explained earlier, new tools have also made it very easy to grade student programs.

Nevertheless, it is easier to run a course without a computational component than with one. The same could be said with even greater force about laboratory experiments. Labs are expensive of space, time, and personnel. Surely it would be preferable not to have labs? The reason labs are normally included despite their expense is because physicists share a conviction that experiment and theory are coequal, and omission of either would shortchange the students. Since in the 21st century computation has become coequal with theory and experiment, it too should play a significant role in the introductory course.

There can be an equipment issue concerned with computation. There needs to be a place, probably in a lab that already has computers for experiments, where students can start a programming assignment in a place where instructors can get them over small hurdles. They may finish the program outside of class, but they need to start it in class. Not only does this help them enormously in getting started but it also ensures some checking that the work is done by the student and not merely copied from someone else. This is similar to the situation with experiments, where a check on the most blatant form of plagiarism is provided by observing students doing the lab.

It is crucial that an instructor using *Matter & Interactions* take the time to become comfortable with new ways of thinking about introductory physics. Much of the emphasis and even some of the physics is unfamiliar, because these aspects of introductory physics have been missing from traditional treatments and don't come up in later courses. For example, instructors need to feel comfortable analyzing circuits directly in terms of the Coulomb interaction, in terms of charge and field, not solely in terms of current and potential.

Initially, instructors reported that the first time they taught *Matter & Interactions* was like teaching a new course, and involved significant extra work compared with simply repeating the traditional course. These early adopters reported that the second time was no more work than usual, and some young faculty who had never taught the traditional course found *Matter & Interactions* to be no more work than did other young faculty who were teaching a traditional course for the first time. Recently however, after the development of a lot more infrastructure including video lectures, some experienced instructors who were new to M&I reported that it was actually easier to teach the new course than the old one.

Occasionally instructors have been tempted to import a few ideas from *Matter & Interactions* into a traditional course. This is usually not a fruitful approach. Students can see that these pieces don't articulate well with the other aspects of the course. For example, telling students to start analyses from fundamental principles is confusing if their traditional textbook advises starting from special-case formula 17.32.

However, it does make sense to carry out a gradual ramp-up in terms of the number of students affected. For example, at Purdue M&I was used in the honors course taken by physics majors for several years before the curriculum was extended to the large engineering course, based on good experience in the smaller scale situation. Initially at NCSU only a few sections of the big engineering course used M&I, and the number of such sections grew as more faculty gained experience with the new curriculum. A similar strategy is being used at Georgia Tech. The main advantage of starting small is that it is much easier to recover from mistakes when small numbers of students and faculty are involved.

Acknowledgements

Supported in part by NSF grant DUE-0320608.

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