FUNDAMENTAL PRINCIPLES IN INTRODUCTORY PHYSICS

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The goal of the contemporary physics enterprise is to explain a broad range of phenomena using only a very small number of powerful fundamental principles. Although instructors and textbook authors may see the enterprise this way, this is not the view typically acquired by students in the calculus-based introductory course. The result of conventional instruction is to reinforce the student's belief that there exists a separate formula for every situation, and that the student's task is to figure out which of these formulas to use. Students may even believe that it is the responsibility of the teacher or the textbook to tell them which formula to use! We have developed a new, modern, curriculum, *Matter & Interactions*, which 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, as are electrostatics and circuits. For additional information, see http://www4.ncsu.edu/~rwchabay/mi.

Introduction

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 analyse 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.

We have created a new curriculum and accompanying textbook, *Matter & Interactions* (Chabay and Sherwood, 2002), which is structured to make clear to students that there is a small number of fundamental principles, which the students themselves can employ to analyse a broad range of phenomena. In mechanics, these are the momentum principle, the energy principle, the angular momentum principle, and the fundamental assumption of statistical mechanics. In electricity and magnetism, we add conservation of charge and the field concept, as expressed in Maxwell's equations. This emphasis on fundamentals permits the integration of topics that have traditionally been kept completely separate. For example, mechanics and thermal physics are intertwined, and both electrostatic and circuit phenomena are analysed using the same concepts and principles. Students are continually asked to analyse new situations, different from ones they have seen before, by starting from these 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 modelling has been done silently by the textbook author. As a part of this 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); aspects of the integration of mechanics and thermal physics are described in Chabay and Sherwood (1999). For additional information about the textbooks and curriculum, see http://www4.ncsu.edu/~rwchabay/mi.

Fundamental principles

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 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 typical rationale given for introductory physics is to learn systematic problem solving, to learn to separate the world into system and surroundings, and to practice applying mathematics. Little 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.

The traditional calculus-based introductory physics course has been unchanged for 50 years and 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 is now characterized as the interplay not only of theory and experiment but also of computation. A serious failing is that the traditional course does not connect to contemporary topics such as materials science, biological physics, nanoscience, astrophysics and cosmology, nonlinear dynamics, quantum computing, condensed matter physics, particle physics, or computational physics.

In the traditional calculus-based introductory physics course the fundamental concepts 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 see as the most fundamental principle in all of physics is $x = (1/2)at^2$, the formula they have used the most.

Traditional instruction focuses on solutions to classes of problems (constant acceleration, circular motion at constant speed, static equilibrium, etc.) rather than on reasoning from fundamental principles. There is a nearly exclusive emphasis on deducing unknown forces from known motion (or lack of motion), with no opportunity for students to experience the power of the Newtonian synthesis, in which motion is predicted from initial conditions and a force law. As a result of this emphasis, students in the traditional course do not see clearly that a small number of fundamental principles can explain a very wide range of phenomena. Rather what comes across to the students is that each situation has its own formula.

During the past 20 years there has been significant research on the learning and teaching of physics, conducted by researchers within the university physics community. One of the central results of this research has been the finding that effective teaching and learning does not come easily, and requires 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 which do in fact improve students' learning of the traditional introductory physics topics.

We argue that it is time to ask a different question: 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 (not just a list of physics topics) needs to be articulated. 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, and macro/micro connections
- Unification of topics, facilitated by the atomic view of matter
- Modeling physical systems, including computational modeling

As an example, in mechanics the fundamental principles are introduced much earlier than has traditionally been the case. The momentum principle is introduced in chapter 1 and used from then on; the energy principle is introduced in chapter 4, the angular momentum principle in chapter 9, and the fundamental assumption of statistical mechanics in chapter 10. This in itself makes the fundamental concepts and associated principles stand out as truly central to the enterprise.

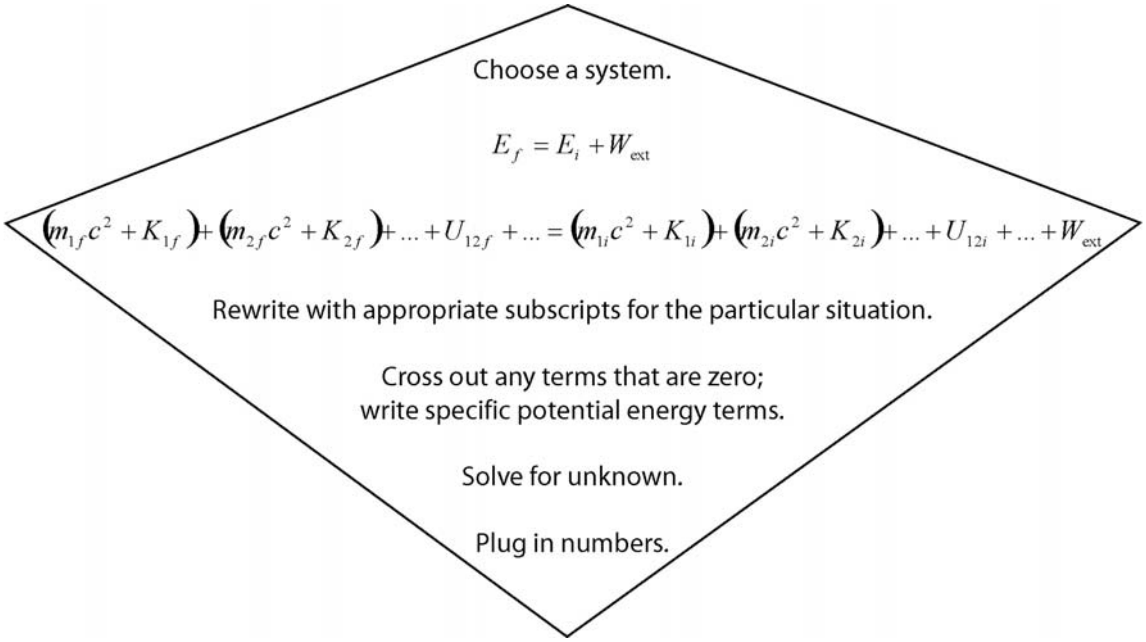
In the traditional curriculum, the momentum principle (Newton's second law) is not actually central. In its general form, it is introduced very late in the course. In *Matter & Interactions* it is introduced immediately in chapter 1 in the form $\vec{p}_f = \vec{p}_i + \vec{F}_{\text{net}}\Delta t$, where $\vec{p} = m\vec{v}/\sqrt{1-v^2/c^2}$. 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. We introduce the Newtonian Synthesis: 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 constrasts 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. We place less emphasis on deducing forces from known motion, such as deducing the support force of an inclined plane on a sliding block.

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 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. To these students, it is not obvious how they will obtain a solution (the desired quantity) by starting with an equation that may not explicitly contain that quantity at all. Thus, 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.

One useful representation was developed by an undergraduate teaching assistant, who himself had taken the course only a year previously (Alex Schriber, personal communication, April

2004). He envisioned the problem solution process as a diamond-shaped flow, first expanding from a fundamental principle, then contracting to a final solution. Many students found this graphic device extremely helpful in clarifying what was meant by starting from a fundamental principle, and indeed were able to apply it to the solution of problems which they had previously found intractable. Here is an example of his ”diamond” approach, starting with the energy principle:



Without this visual guide to the problem solving process, students had typically focused only on the last step: plug numbers into some formula.

Examples of large problems involving modeling

Here are some examples of novel situations which we assign students to analyze as homework problems. Applications of the momentum principle:

- Running students collide (find the force of one student on the other)
- NEAR spacecraft encounters Mathilde asteroid (a detailed statement follows below)
- 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.

Here is the problem statement concerning the NEAR spacecraft mission:

> 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?

These homework problems deliberately transcend the traditional narrow restrictions of introductory mechanics. Classical mechanics taught in isolation is sterile, and can lead to wrong physics. 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 our 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."

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 is an example of a student reflection:

> 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.

A second measurement of students' view of fundamentals was made in a problem-solving study. How students use their knowledge reflects the nature and organization of the knowledge. In a protocol study very difficult, novel problems were posed to volunteer students from a traditional course and to students from an M&I course at the same institution. A striking difference in the two populations was that students from a traditional course tried to map each problem onto a problem whose solution they knew, and/or looked fruitlessly for a formula for the particular situation. In these difficult problems this mapping was inappropriate; for example, students tried to use results from uniform circular motion in analysing an elliptical orbit, or to use constant acceleration results to describe air resistance forces (Chabay, Kohlmyer, & Sherwood, 2002). In contrast, even if they were not able to complete the difficult analysis, all M&I students started from a fundamental principle (Kohlmyer, Chabay, and Sherwood, 2002).

Integration

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. In this section we discuss two examples of such integration: the integration of mechanics and thermal physics (Chabay & Sherwood, 1999), and the integration of electrostatics and circuits. 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.

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 (Sherwood & Bernard, 1984). Does this mean that the energy principle applies only to situations where thermal effects are negligible? Or is it 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, then interpret this phenomenon in terms of the ball and spring model of a solid metal. Through a semiclassical macro-micro argument we obtain 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. Students also study the analytical solution for the motion. From there, we consider a microscopic model of an aluminium wire, considered as a chain of aluminium atoms connected by interatomic “springs”, whose stiffness the students previously determined from Young's modulus for aluminium. 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 aluminium. 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!

As a result of this experience with the ball and spring model of a solid, when the energy principle is introduced it is easy 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 students have previously encountered the idea of discrete electronic energy levels in their chemistry courses, it is an easy step to discussing quantised 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. We state that the quantised harmonic oscillator has evenly spaced energy levels, and students work through several exercises and problems that deal with this system.

With this preparation, students in the introductory course find quite accessible a quantum statistical mechanics analysis (Moore and Schroeder, 1997) of the Einstein solid, a ball and spring model in which each atom is modelled as three independent quantised oscillators. Students write computer programs to calculate the entropy, temperature, and heat capacity of nanoparticles of aluminium and lead. They are asked to fit their curves for heat capacity as a function of temperature to actual experimental data for aluminium 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.

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 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.

Macro-micro connections and the integration of electrostatics and circuits

In the traditional E&M curriculum electrostatics and circuits are treated as almost completely separate topics. Electrostatic phenomena are analysed in terms of charge and field, but circuits are analysed in terms of current and potential, and the connection between these two sets of concepts is not made salient. This dissociation undermines the claim that physics can analyse a wide range of phenomena starting from a small number of powerful fundamental principles. Pedagogically, it also removes the concept of electric field from the student’s view, so that by the end of the course students have often forgotten most of what they learned about this concept in the beginning.

In the M&I curriculum both DC and RC circuits are analysed from a microscopic point of view directly in terms of electric field and the microscopic properties of conductors. The key to this microscopic analysis is the surface-charge model of circuits. This model has appeared in the physics literature for many years but has rarely been mentioned in introductory textbooks (Preyer, 2000). Haertel (1987) brought the explanatory power of this model to our attention and stimulated us to explore ways to make this analysis accessible to students in the introductory calculus-based course. The scheme now works well, and students acquire a deep sense of mechanism for circuit behaviour, including the transient in which the steady state is established through feedback. The subsequent connection of this model to the traditional macroscopic analysis of circuits allows students to reinforce connections between field and potential difference, and to see the microscopic components of macroscopic quantities such as resistance.

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 obviously 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. Quantised energy is introduced to help students link the nature of energy at the macroscopic level to the behaviour of energy in the world of atoms. 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.

Use of the M&I curriculum

The *Matter & Interactions* curriculum is currently in use with students at a variety of institutions within the United States, including small private universities, large state engineering and science universities, four-year liberal arts colleges, and two-year community colleges. Extensive resources are available for instructors who wish to implement this curriculum. For more information, see http://www4.ncsu.edu/~rwchabay/mi.

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