

Rethinking the Content of Physics Courses

Physics students, particularly in today's information age, need to understand the unity of physics and the way in which scientific knowledge is generated.

Diane J. Grayson

During the past 20 years, the focus of physics education research has shifted several times. In the early 1980s, PER was largely concerned with alternative conceptions that students held about various physics ideas.¹ The mid-1980s saw an explosion of interest in computer-based and computer-aided instruction.² In the early 1990s, the PER community published several research-based curricula that promoted activity-based or inquiry-based learning,³ and throughout the decade the community was increasingly focused on student cognition.⁴ As a result of the past two decades of study, physics education researchers know a great deal about how students conceptualize physics and what makes for effective instruction. What is missing is a debate at an international level on the selection of curricular content. In other words, what physics should we teach?

Individual governments usually set kindergarten–12th-grade (K–12) physics curricula; at the university level, textbook authors or individual physicists largely determine curricula. The resulting products are often perceived by students as strings of unrelated topics disconnected from the real world and irrelevant to their daily lives (see reference 5 and the article by Carl Wieman and Katherine Perkins, *PHYSICS TODAY*, November 2005, page 36). At a time when ever-increasing amounts of information are becoming ever more available, and when workplace success is determined more by employees' mastery of transferable skills and emotional intelligence than by their knowledge base, plugging numbers into memorized equations seems like a futile exercise. Unfortunately, many students do experience physics courses as pointless number plugging. Is it any wonder that the number of students majoring in physics worldwide is lamentable?

Changing curricula can help, both in getting K–12 students interested in physics and in keeping them interested at the university level. In July 2004 an international conference took place in Durban, South Africa, under the auspices of the International Commission on Physics Education and the South African Institute of Physics. Its purpose was to provide a forum for physics educators to discuss and debate what should go into 21st-century physics courses at different levels and for different audiences. Participants

and invited speakers, some of whom are shown in figure 1, came from Africa, Asia, Europe, and North and South America to explore seven themes:

- ▶ Overcoming fragmentation in physics
- ▶ Physics for today
- ▶ Blurring the boundaries of physics
- ▶ Conceptual organization
- ▶ Different strokes for different folks
- ▶ Origins and ways of knowing
- ▶ Skills

The conference proceedings run nearly 300 pages,⁶ so a detailed discussion of all that was considered is not possible here. Instead, I shall discuss just some of the ideas that emerged from the conference and their implications for teaching and curriculum development.

Overcoming fragmentation

Traditionally, teachers present physics topics in isolation from one another, sometimes even in different courses. So, for example, mechanics is disconnected from quantum mechanics and thermal physics. Not surprisingly, students fail to see the links among topics and the unity of physics that physicists find so attractive. The difficulty in perceiving essential linkages is only exacerbated by textbooks that provide end-of-chapter questions that refer solely to the contents of a single chapter.

Conference attendees Ruth Chabay and Bruce Sherwood have written a two-volume text that deviates significantly from the traditional approach.⁷ Their first volume includes an integrated treatment of mechanics and thermal physics; the second integrates electrostatics, electric circuits, and electromagnetism. Chabay and Sherwood's approach includes several other important features. It connects microscopic and macroscopic phenomena and explanations, and explicitly links classical and modern physics. It stimulates students to reason from fundamental principles rather than to solve specific classes of problems, and encourages them to model physical systems and use those models to explain complex physical phenomena.

For example, Chabay and Sherwood have students measure Young's modulus for aluminum by stretching a wire. The students then use computer modeling to predict the speed of sound in Al; they treat the wire as a chain of atoms connected by "springs" whose stiffness is determined, with the help of an argument that connects macroscopic and microscopic physics, by Young's modulus. In a subsequent exercise, students investigate how the heat capacity of Al depends on temperature. Proceeding from the Einstein model of a solid, they fit computational curves to experimental data by adjusting the stiffness of the interatomic bond and find that the value they obtained from stretching the wire fits the heat-capacity data.

Corinne Manogue, Kenneth Krane, and colleagues at

Diane Grayson is a professor extraordinarius in the department of physics at the University of Pretoria, South Africa, and director of the consulting firm Andromeda Science Education in Pretoria.



Figure 1. Small group discussions and poster sessions followed each of the seven plenary talks offered at the 2004 International Physics Education Conference held in Durban, South Africa. (Photograph by Kevin Govender, used with permission.)

Oregon State University have developed a physics course whose organization departs even more radically from the traditional approach. It consists of nine three-week modules that deal with cross-cutting themes such as periodic potentials, energy and entropy, and central forces (see the article by Manogue and Krane, *PHYSICS TODAY*, September 2003, page 53).

Viviana Amati and colleagues' conference paper describes how to overcome fragmentation by focusing on how

systems change with time. So, for example, changes in space, temperature, and electrical properties can be treated together rather than in separate chapters on kinematics, thermal physics, and electromagnetism (see the table on this page).

Emphasizing the hierarchical nature of physics ideas also serves to highlight the unity of physics. Physicists think in terms of central concepts and fundamental principles, such as fields and conservation of energy, but beginning students tend to think in terms of disconnected fragments of information all at the same level of importance.⁸ When the hierarchical nature of physics is made explicit to students and they are required to reason from fundamental principles, their learning improves.⁹

Physics for today

Unlike courses in the newer sciences such as biochemistry, many high-school and introductory university physics courses include only topics that are at least 100 years old. Even at higher levels, students are not often exposed to topics with which research physicists are currently engaged. In principle, it need not be too difficult to introduce students to aspects of contemporary physics if the focus is on qualitative interpretations of phenomena and fundamental principles rather than on rigorous mathematical treatments.

If, for example, students have learned about energy levels in atoms and about wave superposition, then it should not take a big conceptual leap for them to learn about the superposition of energy levels in solids, which leads to energy bands. Follow-up discussions could consider the energy-band structure of semiconductors and the host of practical applications that result. Conference participant Dean Zollman has developed a suite of carefully designed computer activities that, among other things, teach students about light-emitting diodes. His program

Unified Mathematical Treatments

Phenomenon	Intensive variable	Equilibrium condition	Equation of change
Height equilibration of liquids in two connected vessels	h	$\Delta h = 0$	$\Delta h = \Delta h_0 e^{-t/\tau} \cos \omega t$
Heat exchange	T	$\Delta T = 0$	$\Delta T = \Delta T_0 e^{-t/\tau}$
Discharge of a capacitor	V	$\Delta V = 0$	$\Delta V = \Delta V_0 e^{-t/\tau} \cos \omega t$

Mathematical similarities among different physical systems bring out the similarities in the physical phenomena. The table illustrates three seemingly different phenomena: height (h) equilibration of two columns of liquid connected with a U-tube, heat exchange between two objects at different temperatures (T), and voltage (V) discharge of a capacitor in an RC circuit. All three phenomena can be described in terms of damped oscillations, as seen in the final column, although the damping for heat transfer is so strong that the oscillatory part is seldom observed. (Adapted from V. Amati et al., ref. 6, p. 92.)

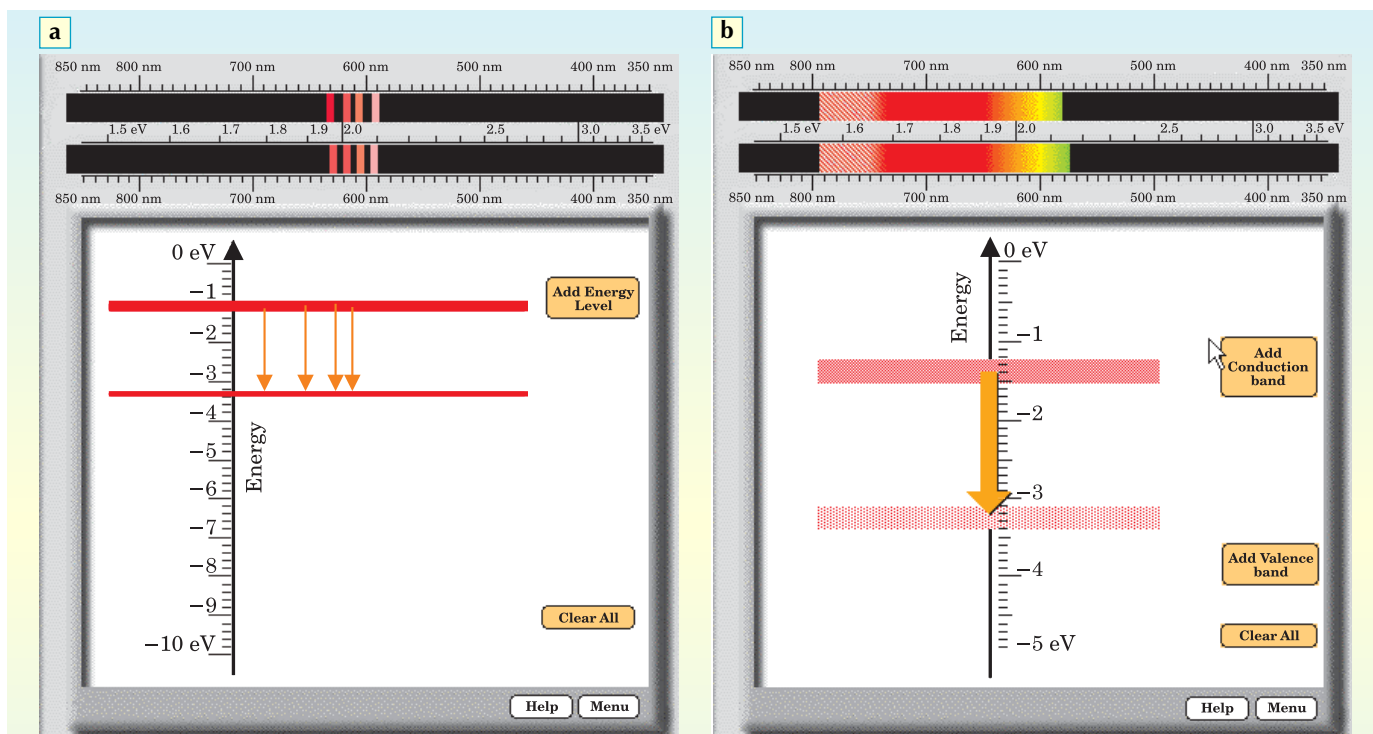


Figure 2. Computer-aided instruction allows students to investigate phenomena that are not directly observable. In this activity, designed by Dean Zollman, students learn how closely spaced energy levels produce the bands responsible for the continuous spectra of light-emitting diodes. **(a)** Students control discrete energy levels so that the lower spectrum they create matches the “empirical” upper spectrum of an unknown gas (in this case, a spectrum made up by Zollman). The closely spaced energy levels corresponding to the closely spaced spectral lines are not resolved in the figure and suggest that energy bands correspond to continuous spectra. **(b)** Students control the conduction and valence bands in order to match the continuous spectrum of an LED. The arrow illustrates a generic transition from the conduction to the valence band. (Adapted from the spectroscopy lab suite available at <http://web.phys.ksu.edu/vqm/software/online/vqm>.)

leads students to conclude that if LEDs are to produce bands of light rather than the line spectra produced by gases, they must have many energy levels that are very closely spaced (see figure 2).

Computation is an important aspect of today’s physics. Research physics has traditionally been divided into two classes, theoretical and experimental. Now the field has a third class—computational physics. That approach to generating knowledge is particularly well suited to such contemporary physics topics as nonlinear dynamics. Priscilla Laws, another physics educator who attended the Durban conference, has her introductory-level university students perform a series of experiments in which they investigate the chaotic motion of a pendulum subjected to several torques simultaneously. Students use a computer to calculate and plot how angular position and angular velocity vary with time.

Blurring the boundaries

Several new interdisciplinary areas of study involve physics. Examples include biophysics (see the article by Ray Goldstein, Phil Nelson, and Tom Powers, *PHYSICS TODAY*, March 2005, page 46), environmental science, materials science, and nanoscience. Such areas provide opportunities for instructors to apply physics principles to new contexts all across the curriculum, and so afford one way to overcome the problem of curricula that contain only

“old” physics. Furthermore, interdisciplinary studies allow research physicists to work collaboratively with people from other disciplines who may think and reason differently. Life scientists, for example, tend to work with complex systems and to concentrate on the interactions among their parts and on the relationships between form and function. The physicist’s approach, on the other hand, tends to be reductionist, seeking a single principle or small set of principles that can explain observed phenomena and predict phenomena not yet observed. Life scientists tend to be expansive in their explanations; physicists are more likely to be parsimonious.

George Ellis’s sweeping view of all of science, both natural and social, extends the theme of blurring the boundaries between physics and other disciplines. In his plenary talk at the conference, Ellis ranked various disciplines in a hierarchy of structure, with physics at the bottom and psychology at the top. As the level in the hierarchy rises, so does the level of complexity of the objects studied by the discipline (see also Ellis’s article in *PHYSICS TODAY*, July 2005, page 49). Emergent properties appear that cannot be determined from lower-level properties; the most complex of them is consciousness. Physicists may be tempted to convey the idea that physics can explain everything. Ellis argues forcefully that it cannot. His line of reasoning brings one naturally to the interface between physics and ethics. Physics principles may determine whether an

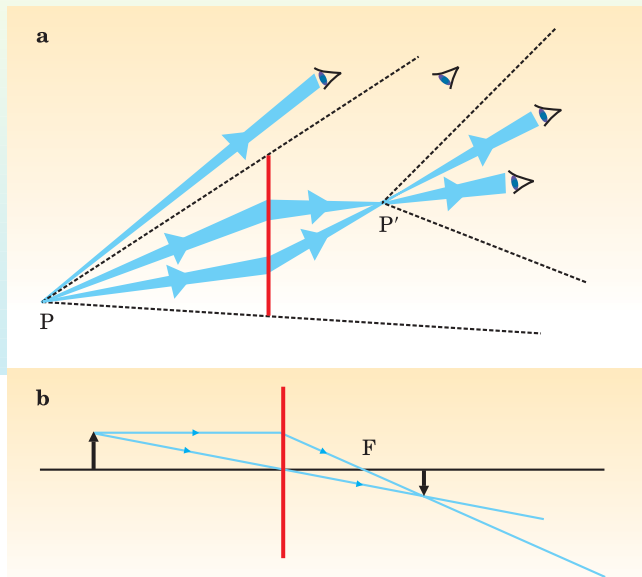


Figure 3. Different representations of optical imaging point students to different features of a lens system. **(a)** This figure stresses the role of the lens (red) as a physical object that bends light passing through it. **(b)** The classic ray diagram, with lens (red) and focal point (F) indicated, shows how to locate the position and size of an image. Introducing (a) before (b) can help students understand two concepts that often cause them trouble: Any part of a lens can form a complete image, and a real image can be formed without a screen. (Adapted from L. Viennot, ref. 6, p. 77.)

atomic bomb will work (bottom-up causality), but a pacifist scientist who gains entry into the bomb-making facility may also determine whether the bomb will work (top-down causality). Promoting classroom debates about ethical issues is an important way to prepare students to be ethical citizens.

Ellis also emphasizes the different ways of thinking involved in disciplines at varying levels of structure. Those differences result in different kinds of explanations and types of causality. An important implication of Ellis's view is that any explanation is only partial, and that the use of one type of explanation in preference to another is a choice based on context. Physics is useful for answering questions of what and how; religion, philosophy, and worldview are useful for answering questions of why. Ellis's argument implies that physics teachers need not set up a confrontation between physics and their students' worldviews; rather, teachers should limit physics explanations to questions that physics can answer.

Conceptual organization

If we who teach physics want to be effective, then what we teach should be influenced by what we know about how students learn. Physics education researchers have convincingly shown that even before they set foot in a physics classroom, students have their own ideas about the world and how it works. Many of those ideas differ greatly from scientific explanations. To make sense to students and lead to meaningful learning, physics curricula should explicitly take into account common alternative conceptions among students and include specific strategies for helping students develop scientifically acceptable understandings. One strategy is to introduce new representations of physical phenomena. For example, plenary speaker Laurence Viennot recommends using figure 3a to introduce students to the function of a lens before showing them the more standard representation depicted in figure 3b.

The sequencing of physics content is also important. Factors that should influence the order in which topics and concepts are taught include their levels of abstraction and complexity and the extent to which they are familiar to students either through daily life experience or previous teaching. In a conference paper, Chabay and Sherwood

propose "A More Coherent Topic Sequence for E&M," which mirrors the presentation of their two-volume text.⁷ They introduce both electric and magnetic fields early on so that students have an opportunity to develop a feel for the field concept and for how fields interact with matter. They also consider electric and magnetic fields in the context of electric circuits, which allows for a microscopic analysis of circuit charges. Only later do they introduce flux, Gauss's law, and Faraday's law. Compared with the traditional ordering of topics, Chabay and Sherwood's sequence reduces the number of new concepts students have to confront in quick succession and gives students the opportunity to work with key concepts in different contexts and to develop physical intuition.

Different strokes for different folks

In an increasingly technological world, a modicum of scientific literacy for all citizens is becoming a prerequisite for both the democratic functioning of societies and the sustainable and responsible use of Earth's resources. To participate meaningfully in debates and decision making about issues that affect us all—including global warming, genetic modification of food, and renewable versus nonrenewable sources of energy—citizens need to understand the process by which scientific knowledge is generated, tested, and modified, and they must be able to judge the trustworthiness of information they obtain. It is indeed useful to understand a few fundamental principles and key concepts and to be able to apply them to a variety of contexts; that is part of learning a scientific way of thinking. But it is more important for citizens to know which questions science can answer definitively and which ones it can answer only tentatively, if at all.

The vast majority of students who take a physics course will not major in the subject. Given that they make up the bulk of physicists' clients, equipping them to function as scientifically literate citizens should be our major concern. The Institute of Physics in London has published a marvelous pair of textbooks that cover the final two years of British high-school physics.¹⁰ They are structured around contemporary themes such as communication, designer materials, and matter in extremes, and are heavy on descriptions and explanations, light on equations. Arnold Arons's classic book, *The Various Language*, has a strong emphasis on helping students understand how scientific knowledge is constructed.¹¹ Such engaging materials are more likely to produce scientifically literate citizens than are the countless textbooks filled with countless equations that weigh down the book bags of countless disconsolate physics students.

Courses for K–12 teachers deserve special mention. Teachers need to know not just physics but also how to make physics understandable to their students. As noted

Figure 4. Emasondosondo, a mobile laboratory, visits schools in rural areas of South Africa so that children whose schools lack laboratories can do experiments. The Zulu word means “the many-wheeled vehicle that brings hope.”

(Photograph by Kevin Govender, used with permission.)



by Lee Shulman, president of the Carnegie Foundation for the Advancement of Teaching, teachers must “be able to explain why a particular proposition is deemed warranted, why it is worth knowing, and how it relates to other propositions, both within the discipline and without, both in theory and in practice.”¹²

Shulman argues that teachers need a special kind of knowledge—pedagogical-content knowledge—that he describes as “subject matter knowledge for teaching.” It includes awareness of likely student difficulties along with effective teaching strategies to address them, and analogies, illustrations, explanations, representations, and demonstrations for making the subject matter comprehensible.

Courses offered for teachers should integrate the development of content knowledge, pedagogical-content knowledge, and epistemological knowledge. And teachers’ courses need to do more than just describe effective teaching; they need to model it. Dale Gundry, one of the conference attendees, created such a course for secondary-school teachers. It emphasizes conceptual understanding, “big ideas” in both classical and modern physics, the socio-political context of nuclear power, the cost of energy, the nature of science, learners’ persistent unscientific ideas, race and gender issues, and laboratory and study skills.

Origins and ways of knowing

Students who have been introduced to history and philosophy of science, and of physics in particular, will better understand how scientific knowledge is created and evolves, and why some knowledge is judged to be scientific and other knowledge—valuable as it may be for cultural reasons—is not. Since all citizens must be able to judge the trustworthiness of the information they receive, it is particularly important that history and philosophy be included in high-school and introductory university courses. Some exemplary textbooks developed in the 1970s included those components^{11,13} but it is not common for modern texts to do so.

Physicists know that all scientific knowledge consists of models created by humans at particular times and places, and that those models evolve or are supplanted as new information becomes available. But it is all too easy to present science to students as if it were a body of incontrovertible facts. A greater focus on the history and philosophy of science will help reveal the dynamic nature of scientific knowledge and will give physics a more human face.

Plenary speakers Igal Galili and Michael Tseitlin make the radical proposal that physics be considered as a set of what they call discipline-cultures, each consisting of a nucleus, a body, and a periphery. The nucleus comprises fundamental concepts and principles, the body comprises applications of those concepts and principles, and the periphery includes elements of knowledge that “conflict with, or cannot be explained by, the statements of the particular nucleus.”¹⁴ Knowledge elements that lie in the periphery of one discipline-culture may lie in the core of another. For example, the Lorentz force lies in the periphery of classical mechanics because it violates Newton’s third law, but it is part of the nucleus of classical electrodynamics. Knowledge elements may also move between the periphery and the nucleus of a particular discipline-culture as understanding evolves and a paradigm shift results.¹⁵

Galili and Tseitlin recommend teaching students to view physics not as a static entity but as a collection of discipline-cultures with knowledge elements that are constantly changing. The students could then see physics as a culture “to be appreciated and explored, rather than a tool to be mastered.” This view, continue the authors, may inhibit students from setting up the sharp mental dichotomy—between human creation and “petrified” material—that they often establish in conventional courses that present one “correct” view.

Skills

Doing physics requires certain skills, and it can also be a vehicle for the development of certain others. Physicists frequently claim that students in their courses learn useful, transferable skills. The claim is often true. But it could be true even more often, and applicable to a greater number of students, if physicists taught a variety of skills as an explicit, integral part of their courses, particularly at the K–12 and introductory university levels. The idea is not new—Arons advocated it 30 years ago.¹⁶ Even so, it is not often implemented: Physics instructors commonly assume that their students will pick up various skills along

the way; consequently, skills acquisition is haphazard.

The more obvious skills that could and should be developed through the teaching of physics include scientific thinking and reasoning, experimental skills, problem solving, and computation. The teaching of skills and content should be interwoven. For example, mechanics can be combined with such skills as translating between graphs and physical phenomena, reasoning in terms of proportions, estimating, and problem solving.

Less obvious skills are “metacognitive”—that is, those that could be developed to monitor and manage one’s own learning. Teachers can help their students develop such skills by, for example, showing them the hierarchical nature of physics, requiring that they discuss the implications of their problem solutions, and requiring them to provide verbal explanations of concepts and phenomena. Skills related to seeking and evaluating information, along with communication skills—both oral and written—are essential not only in physics but in all professions. Students at all levels can develop such skills by carrying out small research projects and presenting their findings both in writing and orally.

Team leaders and team members need a number of skills to function effectively. Those include project planning and management, time management, and interpersonal skills. Gone are the days when scientists of independent means could tinker alone. Cutting-edge research today is a collaborative activity requiring substantial resources. Even if most physics students do not go on to become physicists or researchers, they will still find it useful to acquire a level of competence in the skills required to function as part of a project team. Such skills can be developed through cooperative learning activities in which a group of students must complete a project together.

Graduate students need additional skills. Khalijah Salleh identifies in physics different levels of work, each requiring a specific set of skills: technical, organizational, social, and communicative. In her plenary talk, she observed that the technical level includes theoretical physics, experimental design and data collection, analysis, and applications, and organizational activities entail the establishment of laboratories, formation of research groups, and management of research activities, resources, time, and money. Social activities, she explained, involve interpersonal interaction among members in and outside of the research group, and communication refers to the transfer of information to others.

The classroom, lecture hall, and school laboratory are not the only places, nor necessarily the best places, to learn all the skills discussed above. The physics community should promote alternative settings for learning physics and its associated skills. Possibilities include physics clubs and camps, physics olympiads and other competitions, mobile physics laboratories such as the one depicted in figure 4, and apprenticeships in research laboratories and industry.

Toward a 21st-century curriculum

To this day, physics curricula typically consist of topics whose selection and ordering are guided more by habit or tradition than by cognitive research or sound pedagogy. Fundamental principles and the hierarchical nature of physics knowledge are often not highlighted, with the result that students perceive physics as an impossibly large body of facts and equations to be memorized.

People no longer need to be repositories of large stores of information; that function is better performed by technology. What matters now is how well citizens can access information and what they do with it. In particular, peo-

ple need to make judgments about the reliability of information and when and how to use it. Physics courses that are aimed at the acquisition and routine application of selected information will be largely irrelevant to the needs and interests of 21st-century students.

Physicists have generally maintained that the power of physics lies not in a body of knowledge, useful as that may be, but rather in a way of thinking. Now more than ever, that way of thinking should be the focus of physics courses, even if the detailed course content and emphasis are still a matter of debate. The beauty and power of thinking like a physicist involve identifying which of a small set of fundamental principles and key concepts can be used to describe and predict a broad range of physical phenomena.

Physics also provides a rich context within which to teach a wide variety of skills. In addition to the more obvious cognitive and experimental skills, physics courses could help students develop skills that they will need to function effectively in the modern world. The best way for students to acquire skills is to learn them in a specific context and then transfer them to other contexts. This means that teachers of different physics courses must coordinate their offerings and communicate with each other.

A physics curriculum for the 21st century should include the human dimensions of what is a very human activity, the generation of knowledge about the physical world. That knowledge generation does not take place in a vacuum; it is always embedded in a time and place, influenced by history and culture, passion and prejudice. Students should come away from their physics courses with an increased sense of wonder and excitement at the marvels of the physical world and the ingenious ways in which human beings have tried and continue to try to understand them.

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