The Physics of Energy: 8.21

Robert L. Jaffe and Washington Taylor

Energy is conserved: the first law of thermodynamics tells us that energy can neither be created nor destroyed. Physical processes simply transmute energy from one form to another. In particular, all matter—everything in our world—is a form of energy. Nonetheless, the search for large-scale usable, clean and affordable energy sources increasingly dominates political and economic discourse.

TO UNDERSTAND THE CURRENT ENERGY SITUATION, and to evaluate alternatives for policy, research, investment and technological development, a clear grasp of the basic physics underlying energy processes is essential. Every MIT undergraduate, regardless of their major field of study, should have the opportunity to learn the science necessary to understand the core processes involved in energy systems. This includes the basic physics of technologies such as nuclear reactors, semiconductor photovoltaic cells and wind turbines, as well as the physics of hazards like radiation and global warming associated with some energy sources.

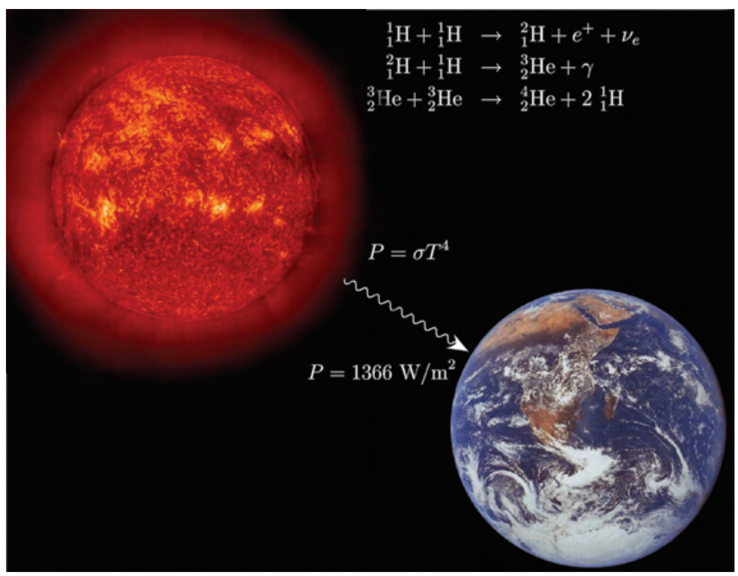
To understand the current energy situation, and to evaluate alternatives for policy, research, investment and technological development, a clear grasp of the basic physics underlying energy processes is essential.

This Fall the physics department will offer a new course, Physics 8.21, "The Physics of Energy." Physics 8.21 is intended for all MIT sophomores, juniors and seniors who want to understand the physical laws and processes that govern the sources, extraction, transmission, storage, degradation and end uses of energy. Physics 8.21 is not aimed specifically at physics majors, but is designed to be accessible to any MIT undergraduate student who has completed the physics, math and chemistry components of the General Institute Requirements, as well as any graduate student with a calculus-based knowledge of mechanics and electromagnetism.

Integrating Theory with Application

The physics of energy involves a close interplay between underlying physical theory and applications. Thus, in 8.21 physical principles are developed in tandem with their applications to energy science. The subject material is loosely divided into three parts, covered sequentially throughout the semester. The first part of the course focuses on end uses of energy. Analysis of basic energy needs such as transport, heating and lighting provide a context for reviewing basic principles of mechanics and electromagnetism. An introduction is then given to aspects of quantum mechanics and thermodynamics that are central to understanding questions in energy physics, such as the limits to efficiency of conversion from heat energy to mechanical energy in an automobile engine.

The second part of the course focuses on sources of energy. This material represents a significant fraction of the course. Further development of quantum mechanics provides the background for understanding fission and fusion reactors and radiation, waste and proliferation hazards. The progress of solar energy is followed from its release in nuclear fusion reactions in the sun, through radiation to the earth and absorption and use in terrestrial systems, integrating material from several branches of physics. This leads to analysis of solar thermal energy plants and development of the basic physics of semiconductors



Most energy used by humans has its origin in the sun. Nuclear fusion reactions in the sun produce energy which is transmitted by electromagnetic radiation to earth. This enormous flux of energy powers almost all earth systems: biological systems, including the origins of fossil fuels; wind, wave and ocean energy systems; as well as human-produced photovoltaics for direct conversion of solar energy into electricity. (Image courtesy of Prof. Thomas Greytak.)

necessary to understand photovoltaic technology (PV), including current silicon-based PV and alternative approaches that may be used in the future. Next, basic fluid dynamics is developed and used to describe the physics of wind and other renewable resources including hydro, tidal, wave and ocean power. Geothermal energy is also discussed. Less time is spent on biofuels and fossil fuels, as the issues here are based more in biology and chemistry, although some important physics aspects of these energy sources are discussed. Basic atmospheric physics and the physics of climate change are covered in several lectures. In the third part of the course, a deeper study of thermodynamics is integrated with a study of energy conversion, storage and transmission methods. The course concludes with a discussion of conservation and an overview of the contemporary energy landscape.

Thematic Unity

As well as providing students with a strong foundation in the science of energy, Physics 8.21 integrates many different subfields of physics, giving students an opportunity to acquire a global picture of how the core ideas of modern physics permeate our understanding of nature and technology. The introductory physics courses 8.01 and 8.02 acquaint students with the fundamental principles of mechanics and electromagnetism. These domains of classical physics, which were well understood in the 19th century, form a foundation for much of modern physical science and associated technology. Most MIT undergraduates who do not major in physics or closely related sciences do not, however, encounter many of the new ideas which have entered physics in the last century. The development of quantum mechanics and the consequent deeper insight into thermodynamics from statistical physics, in particular, has led to a much richer understanding of many physical systems and to many new technologies that will figure in the energy systems of the 21st century. Physics 8.21 introduces and applies those aspects of quantum mechanics and thermodynamics which are relevant for energy systems. The thread of energy ties together physical concepts that would otherwise be encountered in separate courses, and could thus seem disparate and disconnected to students.

Physics 8.21 will provide the scientific foundation for intelligent analysis of the tough political, economic, social and ethical issues which need to be resolved to find sustainable, long-term energy solutions.

Despite the wide range of material covered, 8.21 is not a survey course. The course is focused upon the fundamental physical principles underlying energy processes, and on the application of these principles to practical calculations. Quantitative analysis will be emphasized, and many analytical tools will be introduced and applied which will be new to the students. Physics 8.21 will provide the scientific foundation for intelligent analysis of the tough political, economic, social and ethical issues which need to be resolved to find sustainable, long-term energy solutions. Much of the reading and background material for 8.21 is being created specifically for this course, as existing introductory books and resources on energy physics are written for audiences without the mathematics and physics background of MIT undergraduates.

Outlook

After its debut in the Fall 2008 semester, Physics 8.21 will be offered again in the Fall of 2009 and 2010. The content of the course will undergo a progressive refinement each time the course is taught, aiming for the right balance of theoretical development and practical application to both educate students on the physical principles and enable them to apply their understanding to a wide range of energy systems. This will present an important challenge, both to the educators and to the students. We hope that this course will provide some assistance to the next generation of talented MIT students, who will inherit the greater challenge of developing sustainable energy systems for the future, and who we hope will play leadership roles in facing it successfully.

ROBERT L. JAFFE *is the Jane and Otto Morningstar Professor of Physics at MIT, and the former Director of the MIT Center for Theoretical Physics. Jaffe received his AB in Physics from Princeton, and his MS and PhD degrees from Stanford in 1971 and 1972, respectively. In 1972, Jaffe came to MIT as a postdoctoral research associate in the Center for Theoretical Physics. He joined the faculty in 1974. Jaffe has served on the program advisory committees of several national laboratories and for many years he was the chairman of the Advisory Council of the Physics Department of Princeton University. He now serves as Chair of the Science and Technology Steering Committee of Brookhaven National Laboratory. Jaffe is a Fellow of the American Physical Society and the American Association for the Advancement of Science. Jaffe has been awarded departmental, school and Institute prizes for excellence in teaching, culminating in 1998, when he was named a Margaret MacVicar Faculty Fellow (1998) in recognition of his many contributions to education at MIT.*

Professor Jaffe's research specialty is the physics of elementary particles and quantum field theory, especially the dynamics of quark confinement and the Standard Model. Most recently he

Jaffe / Taylor continued

Jaffe / Taylor continued

has been researching the dynamical effects of the quantum vacuum (Casimir Effects) on micron scales. He has also worked on the quantum theory of tubes, the astrophysics of dense matter and many problems in scattering theory. Jaffe teaches quantum mechanics, field theory, mechanics and electrodynamics at the advanced undergraduate and graduate levels.

WASHINGTON TAYLOR *is a Professor of Physics in the MIT Center for Theoretical Physics (CTP). Taylor received his BA in mathematics from Stanford, and his PhD in physics from UC-Berkeley in 1993. He came to MIT as a postdoc in the CTP in 1993. Taylor joined the faculty at Princeton University in 1995, and returned to MIT in 1998, where he was appointed the Class of 1942 Career Development Professor in 2000, and became a full professor in 2002. Taylor has been an Alfred P. Sloan Research Fellow and a DOE Outstanding Junior Investigator.*

Professor Taylor's research interests are centered on basic theoretical questions related to quantum physics and gravity. His recent work has focused on exploring the large number of apparent solutions to string theory and connections between these solutions and observable particle physics and cosmology. Taylor teaches undergraduate and graduate courses ranging from electromagnetism through quantum field theory.