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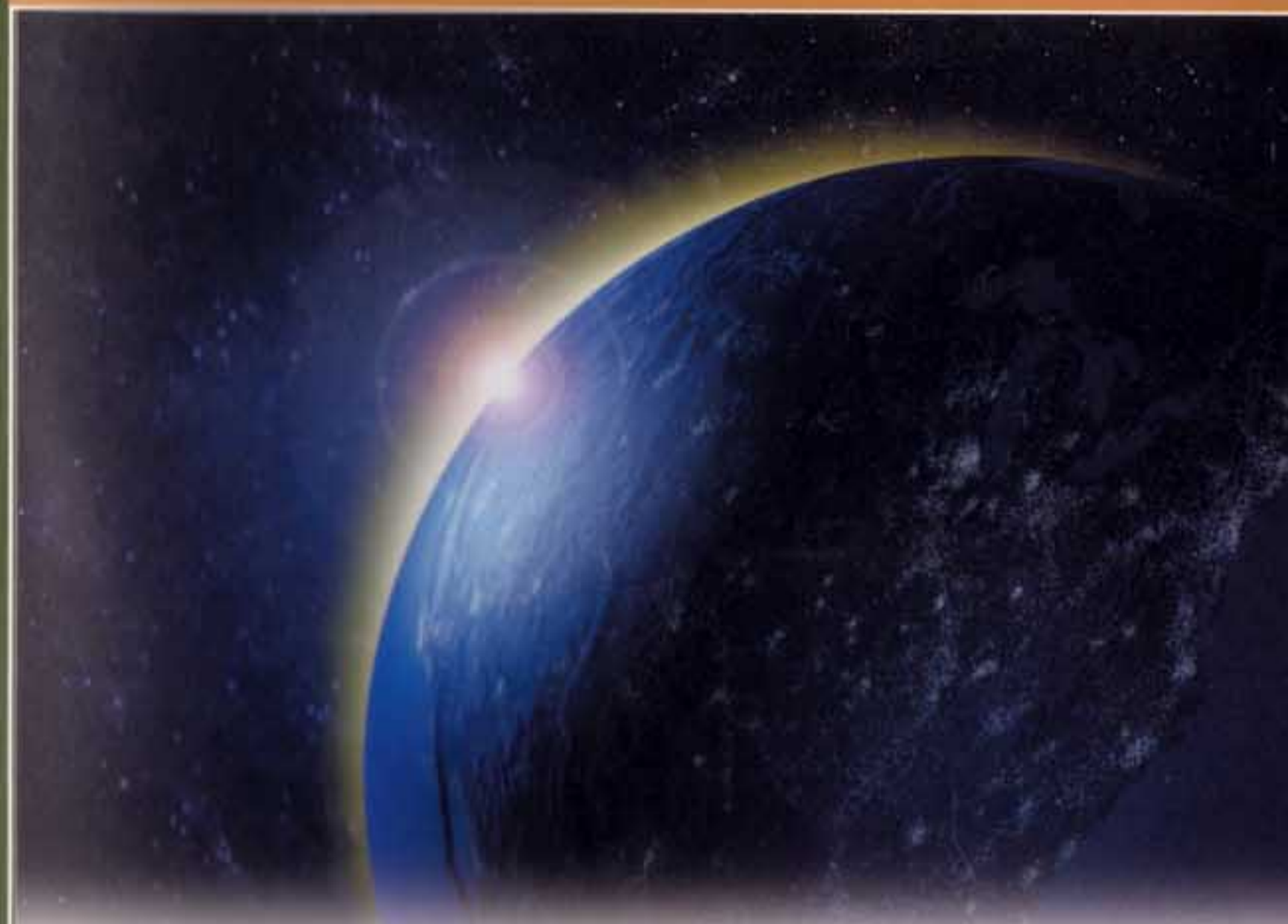
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THE GREAT COURSESSM

Science & Mathematics



Physics in Your Life

Taught by: Professor Richard Wolfson,
Middlebury College

Part 1

Course Guidebook

THE TEACHING COMPANY®

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Richard Wolfson is Benjamin F. Wissler Professor of Physics at Middlebury College, where he has also held the George Adams Ellis Chair in the Liberal Arts. He did undergraduate work at MIT and Swarthmore College, graduating from Swarthmore with a double major in physics and philosophy. He holds a master's degree in environmental studies from the University of Michigan and a Ph.D. in physics from Dartmouth. Professor Wolfson's published work encompasses such diverse fields as medical physics, plasma physics, solar energy engineering, electronic circuit design, observational astronomy, theoretical astrophysics, nuclear issues, and climate change. His current research involves the sometimes violently eruptive behavior of the Sun's outer atmosphere, or corona. He also continues an interest in environmental science, especially global climate change.

Dr. Wolfson is particularly concerned with making science relevant to nonscientists and to students from all walks of academic life. His textbook, *Physics for Scientists and Engineers* (Addison Wesley, 1999), is now in its third edition and has been translated into several languages. His books *Nuclear Choices: A Citizen's Guide to Nuclear Technology* (MIT Press, 1993) and *Simply Einstein: Relativity Demystified* (W.W. Norton, 2003) exemplify Wolfson's interest in making science accessible to nonscientists. He has also published in *Scientific American* and has produced videotaped courses for The Teaching Company, including *Einstein's Relativity and the Quantum Revolution: Modern Physics for Nonscientists*, *Energy and Climate: Science for Citizens in the Age of Global Warming*, and *Physics in Your Life*. Professor Wolfson has spent sabbaticals at the National Center for Atmospheric Research in Boulder, Colorado; at St. Andrews University in Scotland; and at Stanford University.

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Physics in Your Life

Scope:

Physics is the science that governs the workings of physical reality at its most fundamental level. Thus, physics is important in understanding the ultimate nature of the Universe. But it is equally important in our everyday lives. The commonest actions—such as walking, breathing, or driving a car—are all based on principles of physics. The natural world delights us with a host of physics-based phenomena, from rainbows and snowflakes to the blue of the sky, the daily rotation of our planet, and the celestial companionship of the orbiting Moon. And physics-based technology is ubiquitous in modern life—from the CDs and DVDs that entertain and inform us to the antilock brakes that make driving safer, the global positioning system that helps us navigate about our planet, medical imaging that enhances our health, microwaves that cook our food, airplanes that transport us swiftly about the globe, lasers that scan our supermarket purchases, and the semiconductor electronics at the heart of our computers, cell phones, digital cameras, personal digital assistants, and audiovisual systems.

This course introduces principles of physics through their application to everyday life. It's more than a course in physics and more than a laundry list of "how things work." Rather, it combines the two, offering a back-and-forth interplay between everyday applications of physics and the physics principles needed to understand them. Applications include the simplest everyday activities, natural phenomena that affect our everyday lives, and especially, modern technology. Physics principles covered range from Newton's laws of motion, known for hundreds of years but still vitally relevant, to concepts from atomic and quantum physics that underlie such diverse technologies as semiconductor electronics, lasers, and medical imaging.

The course is organized into six modules of six lectures each. The first five modules deal with specific realms of physics and related applications; the sixth is a potpourri of physics applications that draw from more than one of the earlier modules. Although there's no obviously straightforward path through the myriad applications included here, the lectures are designed to build on each other and to flow smoothly from one to the other. *Physics in Your Life* is aimed at intelligent nonscientists, and the presentation of physics concepts and applications is entirely nonmathematical.

Given that the course is presented on audiovisual media, the first module—**"Sight and Sound"**—begins with the technology behind CDs and DVDs, not only explaining how these work but raising questions that lead to the basic principles of light and sound. Subsequent lectures explore these principles in application to such diverse topics as rainbows, optical fibers for communications, musical instruments, and laser vision correction.

“Going Places” looks at motion and its applications, from simple walking to modern automobile technology, airplane flight, and space travel. This module is based on Newton’s laws, generalized to include such diverse topics as fluid motion, conservation of energy, and the dynamics of space flight from communications satellites to interplanetary exploration.

“Plug In, Turn On” explores the electromagnetic basis of so many contemporary technologies and natural phenomena. Matter itself sticks together through electrical interactions, while the intimate relations between electricity and magnetism are at the heart of technologies ranging from electric motors and generators to videotapes and credit cards. We’ve learned numerous ways to produce electrical energy, and we respect not only the good it can do but also the dangers it poses. Finally, electricity and magnetism join to make possible the electromagnetic waves that include visible light and that enable the growing host of wireless technologies in our everyday lives.

“From Atom to Computer” starts with basic ideas in atomic physics and builds through explanation of the semiconductor materials at the basis of today’s electronics; the operation of the transistors that are the essential electronic components; the agglomeration of close to a billion transistors in today’s most sophisticated integrated circuits; the simple logical operations that underlie all our computers can do; and the structural organization of an entire computer.

The fifth module, **“Fire and Ice,”** introduces concepts and applications related to heat. Lectures range from “Physics in the Kitchen” to “Life in the Greenhouse,” the latter a look at how principles of thermal physics establish Earth’s climate and how we humans may be changing that climate. “The Tip of the Iceberg” describes the thermal response of materials, including the unusual behavior of water in both liquid and solid form—a behavior with enormous implications for life on Earth. The module ends with a look at humanity’s appetite for energy in the face of limitations posed by the laws of thermodynamics. Those laws themselves are the subject of “Like a Work of Shakespeare,” a lecture so titled because one such law has been deemed as essential to an educated person as the Bard’s writings.

The sixth module is a potpourri of applications and principles from the specific to the cosmic. “Your Place on Earth” describes the workings and increasingly pervasive applications of the space-based Global Positioning System (GPS). “Dance and Spin” looks at applications of rotational motion from dance to pulsars. “The Light Fantastic” explores the operation of lasers and their applications in everything from supermarket scanners to the Internet. “Nuclear Matters” looks at the behind-the-scenes roles that nuclear physics plays in our lives. “Physics in Your Body” emphasizes modern medical techniques, such as MRI and particle-beam treatments for cancer. The course ends with “Your Place in the Universe,” tracing the history of your own body from the earliest events of the Big Bang.

Lecture One

Realms of Physics

Scope: Physics is the fundamental science, describing the workings of physical reality on scales from subatomic to cosmic, in times from unimaginably tiny fractions of seconds to billions of years. We humans, in size and lifespan, are somewhere in the middle of this vast range. Physics touches our everyday lives—from the most commonplace acts, to the sophisticated technologies that we take almost for granted, to the natural phenomena that shape our environment. This course explores a great many of the ways in which physics connects with your life, providing not only a smorgasbord of physics applications but also a grounding in the underlying principles and fundamental laws of nature.

Historically, physics divides into two great realms, classical and modern. Classical physics, firmly established by the year 1900, nevertheless remains vitally relevant to much of everyday life. Modern physics extends our understanding to realms of the very small, the very fast, and the very massive through the theories of quantum physics and relativity. Despite these arcane contexts, modern physics is at the heart of much everyday technology. Physics also divides by subject: There are the physics of motion, or mechanics; electricity and magnetism; optics and light; the physics of heat and other thermal phenomena; and the extensions of these branches to the atomic scale. This course is loosely organized into modules based on these subject realms, starting, appropriately for an audiovisual-based course, with the physics of sight and sound and moving through motion; electricity and magnetism; the atomic and other physics behind electronics, especially computers; and the physics of heat and energy. Each module emphasizes applications in everyday life, grounded in basic principles. A final module presents a potpourri of applications that blend ideas from earlier in the course.

Outline

- I. Physics *is* in your life! All everyday activities involve physics.
 - A. All involve your interacting with physical reality—either human-made technology or the natural environment.
 - B. That’s what physics is about: the nature and workings of physical reality.
 - C. Knowing physics in its application to everyday things enhances your understanding and appreciation of the world around you. It may also make you a wiser user of technology and a better steward of the natural world.

- D. Motivation for this course is to explore applications of physics in your everyday life, involving both technology and natural phenomena. This is not a standard physics course, nor simply a “how things work” explication, but a combination of the two. You’ll come out of the course understanding not only the workings of many everyday phenomena but also the physics principles behind them.
- II. Physics encompasses a range of interrelated realms, distinguishable by the specific sorts of physical phenomena described or by historical context. All realms of physics have some bearing on the physics of our everyday lives, but most of everyday physics falls under the realm of *classical physics*.
- A. *Classical physics* refers to the understanding of physical reality developed before about 1900. Although long established, classical physics is still very much alive and contemporary. It’s classical physics that lands robot explorers on Mars, explains airplane flight, or dictates the operation of antilock brakes and automotive stabilization systems. Classical physics comprises several subfields:
1. *Mechanics* is the study of motion. Developed by Isaac Newton some 300 years ago, classical mechanics applies to systems ranging from roughly the size of molecules up to stars and galaxies. The human-scale realm falls roughly in the middle of this vast range.
 2. *Electromagnetism* encompasses two previously distinct areas of study: electricity and magnetism. Electromagnetism is at the basis of all our electrical and electronic technology. Light, radio, TV, microwaves, infrared, ultraviolet, and x-rays are all waves whose nature is fundamentally electromagnetic.
 3. *Optics* is the study of light and its behavior. Ultimately, classical optics is a branch of electromagnetism, but it is often explored as a separate subject. Classical optics tells us how to build instruments ranging from microscopes through eyeglasses and contact lenses to telescopes. Principles of optics dictate the reshaping of the cornea in laser vision correction. And optical phenomena are widespread in nature. Many of the principles of optics apply as well to sound.
 4. *Thermodynamics* is the study of heat and related phenomena. Among other things, principles of thermodynamics tell us how to keep warm in the cold and cool in the heat; determine Earth’s climate and the changes we’re causing in the climate; and show why we can’t build perfectly efficient engines and power plants.
- B. Although classical physics does an excellent job describing many everyday phenomena, classical ideas break down in three realms: the very small, the very fast, and where gravity is very strong. These realms demand new descriptions of physical reality, which were developed early in the 20th century and are called, collectively, *modern physics*. Classical physics can be considered an approximation to the more accurate descriptions of modern physics, an approximation that is

perfectly adequate in most everyday physics. The ideas of modern physics are covered in the Teaching Company course *Einstein’s Relativity and the Quantum Revolution: Modern Physics for Nonscientists*.

1. *Special relativity* deals with objects moving at high speeds relative to one another. Here, *high speed* means speeds approaching the speed of light. Because everyday objects don’t move with such speeds relative to us, special relativity is of limited applicability in everyday physics—although on rare occasions, it must be considered.
2. *General relativity* subsumes special relativity and describes gravity. The predictions of general relativity differ from Newton’s classical theory of gravity only when gravity is very strong—such as near black holes or in the early Universe—or when considering the large-scale structure of the Universe. Differences between classical physics and general relativity are difficult to detect in our solar system, although one technological application—the Global Positioning System—is so sensitive that general relativity must be taken into account. Philosophically, relativity radically alters our notions of space and time, but again, those alterations are not significant in most everyday phenomena.
3. *Quantum physics* describes nature at the smallest scales—generally, the size of atoms and smaller. As such, quantum physics is ultimately at the basis of all everyday phenomena, because quantum principles determine the structure of atoms and how they join to make the myriad substances we deal with every day. And quantum principles are at the basis of everyday technologies, such as semiconductor electronics and lasers.
4. An ultimate goal is to understand all of physical reality in terms of a single *Theory of Everything*. Physicists have made great strides here, as in the merging of electricity and magnetism, followed by optics, under the rubric of electromagnetism. But we aren’t there yet; in particular, no one has yet figured out how to reconcile quantum physics with general relativity. As a result, we don’t have an adequate description of small-scale phenomena in the presence of strong gravity—as happens at the center of a black hole or in the very early Universe.
5. Although physics has been successful in explaining nature and developing new technologies, there’s reason to be humble: Recent astronomical observations coupled with elementary-particle theories confirm that at most about 5 percent of the Universe is composed of matter as we know it. The rest consists of mysterious *dark matter* and *dark energy*, about which we know almost nothing!

III. Back to everyday physics: The course is divided into six modules of six lectures each. The first five modules each correspond to a particular area of physics or related technology; the last is a potpourri of physics applications that generally draw on more than one of the preceding modules. Each lecture introduces a mix of physics principles and everyday applications. The approach is entirely qualitative—no math! (Although the “Going Deeper” readings may involve math.) We start with Module One, “Sight and Sound,” because this is an audiovisual-based course. As a disclaimer, keep in mind: There’s far more “physics in your life” than will fit into 36 half-hour lectures! Here’s an outline:

A. Module One: Sight and Sound

1. Lecture Two (Lecture One is this introduction): The Amazing Disc
2. Lecture Three: The Wonderful Wave
3. Lecture Four: Seeing the Light
4. Lecture Five: Is Seeing Believing?
5. Lecture Six: Music to Your Ears

B. Module Two: Going Places

1. Lecture Seven: May the Forces Be with You
2. Lecture Eight: Aristotle’s Revenge
3. Lecture Nine: Going in Circles
4. Lecture Ten: Taking Flight
5. Lecture Eleven: Into Space
6. Lecture Twelve: A Conservative Streak

C. Module Three: Plug In, Turn On

1. Lecture Thirteen: The Electrical Heart of Matter
2. Lecture Fourteen: Harnessing the Electrical Genie
3. Lecture Fifteen: A Magnetic Personality
4. Lecture Sixteen: Making Electricity
5. Lecture Seventeen: Credit Card to Power Plant
6. Lecture Eighteen: Making Waves

D. Module Four: From Atom to Computer

1. Lecture Nineteen: The Miracle Element
2. Lecture Twenty: The Twentieth Century’s Greatest Invention?
3. Lecture Twenty-One: Building the Electronics Revolution
4. Lecture Twenty-Two: Circuits—So Logical!
5. Lecture Twenty-Three: How’s Your Memory?
6. Lecture Twenty-Four: Atom to Computer

E. Module Five: Fire and Ice

1. Lecture Twenty-Five: Keeping Warm
2. Lecture Twenty-Six: Life in the Greenhouse
3. Lecture Twenty-Seven: The Tip of the Iceberg
4. Lecture Twenty-Eight: Physics in the Kitchen
5. Lecture Twenty-Nine: Like a Work of Shakespeare

6. Lecture Thirty: Energy in Your Life

F. Module Six: Potpourri

1. Lecture Thirty-One: Your Place on Earth
2. Lecture Thirty-Two: Dance and Spin
3. Lecture Thirty-Three: The Light Fantastic
4. Lecture Thirty-Four: Nuclear Matters
5. Lecture Thirty-Five: Physics in Your Body
6. Lecture Thirty-Six: Your Place in the Universe

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 1.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 1.

Questions to Consider:

1. Give several examples of everyday technologies that are clearly based in physics, and try to identify the realm of physics that’s most relevant to each.
2. Give several examples of natural phenomena that are clearly based in physics, and try to identify the realm of physics that’s most relevant to each.

Module One: Sight and Sound

Lecture Two

The Amazing Disc

Scope: The compact disc and its cousin, the DVD, provide a virtual metaphor for all of physics. Discs rotate, as do objects from car wheels to planets. They store information, a role they have in common with magnetic tapes, credit-card strips, semiconductor electronics, phonograph records, and DNA molecules. They're read with an optical system that involves lasers and the reflection, refraction, and interference of light. The stream of information coming off the disc is manipulated by physics-based electronic circuitry and, finally, using a variety of physics principles, converted to light and sound for your eyes and ears. You're most likely viewing this course on a DVD, and even if you aren't, these devices almost certainly play a role in your life (we'll get to VHS videotape in a later lecture). The processes involved in recording and playing a CD or DVD provide examples of many fundamental principles of physics. This lecture introduces these amazing discs as a way of opening a window into the broader realms of physics.

Outline

- I. The course's first module, "Sight and Sound," explores everyday phenomena based on the behavior of light waves and sound waves. This first lecture uses compact discs and DVDs as metaphors for the whole realm of physics, especially for the phenomena of light and sound.
 - A. For viewers and listeners with tapes—we'll cover those, too, but later.
 - B. Motion: Discs rotate, and they do so with varying speed—why?
 - C. Discs are an *optical storage medium*. They involve lasers and the reflection, refraction, and interference of light waves.
 - D. Disc information is processed electronically. This involves semiconductors, whose operation is governed by atomic and solid-state physics.
 - E. Discs deliver sound and visible images. This involves the behavior of sound waves and the focusing of light in technological systems and the human eye.
- II. History: CDs and DVDs culminate a long history of audio and video storage systems. Viewers can date themselves by their first audio technology! These include wax cylinders, wire recorders, 78-rpm records, long-playing records, reel-to-reel tape, and audio- and videocassettes.
- III. The amazing disc: A quick look gives insights into this technology but also

raises more questions whose answers lie in underlying principles of physics. Here, we concentrate on information storage and retrieval with the CD, but the same concepts apply to the DVD.

- A. Information on a CD is stored *digitally*, allowing undiminished quality every time the disc is played. Digital storage contrasts with the analog storage used in most audio- and videotapes and older systems, such as phonograph records. With these, quality degrades over time. In contrast to analog, digital storage also permits identical copies to be made and transmitted over computer networks, with no degradation in quality. That's a big cause for concern in the recording industry.
 1. In digital devices, all information is stored as sequences of the digits 0 and 1—that is, as numbers in the binary (base-2) number system. This course, as stored on a disc, is nothing more than a very long binary number! So is a computer program or a digital camera image. The 1s and 0s are called *bits*; a sequence of 8 bits makes a *byte*. On a CD, sequences of 16-bit numbers give the intensity of sound at successive times; the CD holds 44,100 such numbers for each second of recorded music (actually 88,200 because of two stereo channels, stored in a more complicated coding scheme). Those 16 bits provide 2^{16} , or about 66,000 different sound intensity levels.
 2. The 0s and 1s can be coded as electrical switches that are off or on in a computer memory, as oppositely magnetized regions on a cassette tape, or as spots that alter the reflection of light on a disc.
 3. Digital systems are robust and free from interference because all the system needs to do is recognize the difference between 0 and 1. There are no "shades of gray" in between.
- B. On the CD and DVD, digital information is in the form of tiny "pits" stamped into the plastic of the disc and covered with a thin layer of metal.
 1. The pits are tiny, ranging in size from 1–3 millionths of a meter in length, and are half a millionth of a meter wide. (A human hair is about 100 millionths of a meter in diameter.) The pits lie in spiral tracks about 1.6 millionths of a meter apart. There are about 22,000 tracks on a CD, with a total length of more than 3 miles! The number of pits determines the amount of information stored—about 74 minutes of audio or 640 million bytes of computer data on a standard CD. Hold up a disc and you see a rainbow of light coming from the pits and tracks. (Physics question: Why the rainbow? See Lecture Five!)
 2. The information is read with a laser beam whose light reflects from the shiny metal of the disc. (Physics question: How's that laser work? That's the subject of Lecture Thirty-Four.) Because the pits are stamped from above but the disc is read from below, the pits

appear to the laser beam as raised areas. The beam is somewhat larger than the width of the pits. When the beam hits a flat area between pits, it's all reflected. But at a pit edge, interference and scattering of light waves diminishes the intensity of reflected light. Thus, the presence of the pits produces a pattern of varying light intensity, and that's what conveys the information on the disc. (Physics question: Interference—how's this work? Next lecture!) Each pit edge represents a digital 1; the areas in between, a digital 0.

3. The varying-intensity light beam is converted to an electronic signal and processed to drive a loudspeaker or video display.
4. One big advantage of the CD over previous information storage systems is that it's almost completely immune to dust—remarkable given the tiny size of the information-storing pits. This feature results from the focusing of the laser beam as it passes through the plastic of the disc. At the point it enters the disc, the beam is 500 times larger than it is at the information layer; thus, dust particles far larger than the pits don't affect the beam significantly. (Physics question: How does focusing occur? Lecture Four!)

C. Related technologies include recordable discs and DVDs.

1. Recordable CD-R discs use chemical dyes that become opaque when a high-power laser beam hits them. That laser “burns” the information onto the disc, and when the disc is “read,” the lower power pickup laser again detects the differences between light and dark regions. Re-recordable CD-RW discs are similar but use a material whose crystal structure changes when exposed to the laser. Because this process is reversible, the disc can be used many times.
2. DVDs use smaller pits, more closely spaced tracks, and more efficient storage schemes to fit seven times as much information on a disc the same size as a CD. And discs that first appeared commercially in 2003 will provide more than 30 times the information capacity of the CD. (Physics question: What allows the much greater capacity of DVDs and more advanced discs? Next lecture!)

D. Summary: CDs and DVDs are amazing devices, made possible with the application of basic physics principles—especially in the fields of waves, optics, and sound. In the remainder of this module, we explore these fields and their applications in other everyday phenomena, from rainbows to laser surgery, police radar to music. In the process, we will answer the many basic physics questions raised in our quick survey of the amazing disc.

Suggested Reading:

Ken C. Pohlmann, *The Compact Disc: A Handbook of Theory and Use*, chapter 1.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 16, section 3.

Going Deeper:

Ken C. Pohlmann, *The Compact Disc: A Handbook of Theory and Use*, chapters 2–4.

Jim Taylor, *DVD Demystified*, chapters 1–3.

Questions to Consider:

1. Why do digital storage media, such as CDs and DVDs, create a much greater threat of copyright violation than analog systems, such as audio- and videocassettes?
2. Can you think of any ultimate limit to the amount of information that might be stored in a given space?

Lecture Three

The Wonderful Wave

Scope: Light and sound—the subjects of this first module of lectures—are both examples of waves. Others include ocean waves; waves that carry the energy released in earthquakes; the microwaves that cook your food, connect your wireless computers, enable the police to catch you speeding, and provide astrophysicists with an echo from the beginnings of the Universe; the ultrasound that doctors use to probe your innards; and even the wave of standing people that sweeps through a football stadium. All these waves have common properties, and they exhibit similar behaviors. Those behaviors determine what and how we see and hear, the design of optical instruments and our own eyes, the information storage capacity of CDs and DVDs, natural phenomena such as rainbows, the construction of musical instruments and architecture of concert halls, and a host of other technologies and natural phenomena. This lecture explores basic wave behaviors and properties and sheds light on a number of everyday phenomena.

Outline

- I. Most of our contact with and knowledge about the world comes from *waves*. Sight and sound involve waves. So do many technological systems, especially for communication. And our knowledge of the Universe beyond Earth comes almost exclusively from electromagnetic waves, including light.
 - A. What's a wave? It's a disturbance that transports energy but not matter. Example: Watch a boat bobbing on ocean waves. As the waves sweep shoreward, the boat just moves up and down—it isn't carried along with the waves. Neither is the water itself.
 - B. Waves are characterized by several distinct properties:
 1. *Amplitude* is the size of the disturbance. For sound, amplitude measures variations in air pressure; the greater these variations, the louder the sound. For light, amplitude measures the strengths of electric and magnetic fields that constitute the wave; the larger these fields, the brighter the light.
 2. *Wavelength* is the distance between successive wave crests. For sound, shorter wavelengths correspond to higher pitch. For light, shorter wavelengths correspond to bluer light; longer wavelengths to redder light. The wavelength of visible light is tiny—about half a millionth of a meter (half a thousandth of a millimeter)!
 3. Waves travel with a particular speed. For sound, that speed depends on the properties of the air and is approximately 340

meters per second—about 700 miles per hour or 1,000 feet per second. For light in air or vacuum, the speed is some 300,000 kilometers per second, or 186,000 miles per second. The huge difference between light and sound speeds accounts for the “5-second” rule for determining the distance to a lightning strike. The speed of sound also sets the upper limit for the speed of most commercial aircraft.

4. The time between successive wave crests is the *wave period*. The number of wave cycles in each second is the *frequency*, which is simply the inverse of the period. The wave travels one wavelength in each period; thus, the wave speed is simply the wavelength divided by the period or the wavelength multiplied by the frequency. The frequency of AM radio is about 1 million cycles per second (1 megahertz, Mhz), while visible light has a frequency of about 500 trillion cycles per second.

II. All waves exhibit some common behaviors.

- A. Waves *reflect*, or bounce off material surfaces. Reflection from a rough surface results in waves coming off at different angles; this is called *diffuse* reflection. Reflection from a smooth surface, such as light from a mirror, is *specular* reflection. Here *smooth* means that variations in the surface are typically smaller than the wavelength of the waves. Most vision depends on diffuse reflection of light off objects that themselves do not give off light. Reflection of sound determines the acoustical properties of concert halls (more in Lecture Five).
- B. Waves *refract*, changing direction when they enter new materials. This occurs because waves travel at different speeds in different materials—just as a row of marchers in a parade turns when the marchers on one side slow down. This helps explain the focusing of laser light entering the clear plastic of a CD or DVD and shows that the plastic used in making discs must have the same carefully controlled optical properties. Refraction is also responsible for image formation, including in our eyes, as well as for such phenomena as mirages (more in subsequent lectures).
- C. Waves *interfere*. Unlike material objects, two waves can be in the same place at the same time. When that happens, the disturbances associated with the two waves simply add. This interference can be *constructive* (waves reinforce) or *destructive* (waves cancel).
 1. Question: Suppose you had two waves that were in step. You separate them and make one travel a bit farther than the other so that when you bring them together again, they're no longer in step. How much farther would the one wave have to travel in order that its troughs would line up with the first wave's crests, resulting in totally destructive interference?

Answer: Half a wavelength difference will bring the waves together crest-to-trough, so they'll cancel completely. That answers our question about how a CD player detects the pit edge that represents a digital 1—and it also says that the pits should be about one-quarter wavelength deep. The total round-trip path for light hitting a pit versus light not hitting a pit is one-half wavelength, resulting in destructive interference.

2. Wave interference also explains those rainbows you see on the shiny side of a CD. At a certain angle, light reflecting off two successive tracks on the CD will travel exactly a wavelength more in reflecting off the more distant track. The light reflecting at this angle off all the tracks will interfere constructively, making a bright reflected beam. Because different colors have different wavelengths, this happens at different angles for different colors—hence, the rainbow.
3. Another example: Waves in a microwave oven have wavelengths around 10 centimeters, or about 4 inches. Destructive interference would result in “cold spots” where the food wouldn't cook. To avoid this, ovens rotate the food or have a rotating reflector to keep changing the position of the cold spots.

D. Waves *diffract*, or change direction as they go around objects. This effect isn't very obvious with large objects, but when an object is as small as the wavelength of the waves, it becomes a big effect. As a result, it becomes impossible to see or otherwise detect objects smaller than about a wavelength in size. This is called the *diffraction limit*.

1. The diffraction limit answers our question about information storage on CDs and DVDs. When CDs were invented in the early 1980s, the only small, inexpensive lasers available put out infrared light; CD makers settled on light with a wavelength of 0.78 micrometers (millionths of a meter). The size of CD pits, about 1–3 micrometers long by half a micrometer wide, in tracks about 1.6 micrometers apart, is about the smallest that can be reliably “seen” with this wavelength. DVDs, in contrast, use red laser light, with wavelength of about 0.65 micrometers. Thus, the pits can be smaller and more closely spaced—accounting for most of the improvement in information storage over the CD. The “Blu-ray” discs first introduced in 2003 use a blue laser at about 0.40 micrometers. The lower diffraction limit accounts for their vast capacity (some five times that of a conventional DVD).
2. Diffraction of sound waves explains why the bass notes from loud music travel better through buildings than do high notes. Obstructions, such as corners or door openings, are much smaller than the long wavelengths of bass notes, so those waves diffract around corners and through doors. But the shorter wavelengths of

high notes diffract much less, so they don't get around corners and through doors.

3. Bats provide yet another example of the diffraction limit. They detect their food—insects—with reflected sound. But the size of an insect is smaller than the wavelength of the sound waves audible to humans, so they couldn't be detected with audible sound. Therefore, bats emit shorter wavelength ultrasound that we humans can't hear.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapters 19, 29.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 16.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapters 16 and 37.

Questions to Consider:

1. The smallest biological structures in cells cannot be imaged with conventional microscopes using visible light. Why not? (Electron microscopes are used instead.)
2. The physical placement of a “subwoofer” loudspeaker that handles the lowest bass tones in a home audio system is much less critical than the placement of speakers that handle the higher frequencies. Why the difference?
3. If the wavelength of microwaves used in a microwave oven were tiny—say, less than a millimeter—would it be important to rotate the food while it's cooking?

Lecture Four

Seeing the Light

Scope: Light makes possible what is for most of us our primary way of perceiving the world. Our eyes do more than just detect light; they form images, giving us a visual representation of our surroundings. A variety of technologies, from telescopes to microscopes, CD players to still and video cameras, also make use of image formation. And when our own eyes fail us, image-forming technologies come to the rescue with eyeglasses, contact lenses, and laser surgery. Finally, modern technologies capture, store, and display images for our convenience. In this lecture, we explore the processes of image formation and image capture as they follow from basic properties of light.

Outline

- I. The key to image formation is *refraction*, the bending of light at an interface between two transparent materials. The preceding lecture showed why refraction occurs; here, we exploit refraction to form images.
 - A. A *lens* is a piece of transparent material shaped so that parallel light rays bend to reach a common point—the *focal point*.
 1. The distance from the lens to the focal point is the *focal length*. The shorter the focal length, the stronger the lens. The *diopter* measure used for eyeglasses and contact lens prescriptions is simply the inverse of the focal length in meters. For example, my +2.00 contact lenses have a focal length of 1/2.00 meter, or half a meter.
 2. For an ideal lens, any light ray parallel to the lens axis is deflected through the focal point. Any ray passing through the center of the lens is undeflected. Those facts are sufficient to understand image formation.
 3. Real lenses suffer a variety of defects and distortions, especially astigmatism and color distortion.
 - B. Understanding how lenses form images is as simple as drawing two rays from an object being imaged, one parallel to the lens axis and the other through the center. The former is deflected through the focus; the latter, undeflected.
 1. An object farther from the lens than the focal length forms a *real image*—an image at which light is actually present. Examples include the image on a movie screen and the image that forms on the retina at the back of your eye.
 2. An object closer to the lens than the focal length forms a *virtual image*, from which it only appears that light is coming. This is the

sort of image you see when you use a simple lens as a magnifying glass.

3. These considerations apply to convex lenses, which are thicker in the center than at the edges. Concave lenses, in contrast, cause light rays to diverge and can form only virtual images. They are characterized by negative focal lengths, which show up in prescriptions for eyeglasses and contact lenses.
 - C. In your eyes, the cornea provides most of the refraction that forms images; behind it, the flexible lens adjusts to compensate for objects at different distances. As you age, that lens loses its flexibility. A properly functioning eye forms sharply focused images on the retina, where light receptors send the information via nerves to the brain.
 1. A farsighted eye is too weak and the image forms behind the retina, giving a blurred picture on the retina. How might this be corrected? The answer is by putting a convex lens in front of the eye.
 2. A nearsighted eye is too strong, and the image forms in front of the retina. How might this be corrected? Put a concave lens in front of the eye.
 3. Laser surgery provides more permanent vision correction, reshaping the cornea by ablating away portions of corneal tissue with precisely controlled ultraviolet light. The procedure is most successful for nearsightedness, where the cornea is too thick at the center and easily thinned down.
 - D. Optical instruments, such as microscopes and telescopes, use lenses (or mirrors, in astronomical telescopes) to form images; these images, in turn, are viewed with a second lens called the *eyepiece*. In microscopy, the diffraction limit introduced in the previous lecture prevents the use of visible light for imaging very small structures—hence, the development of electron microscopes and other newer imaging technologies.
- II. We capture and save images using lenses to focus images onto “memory substances” that include old-fashioned film and a variety of newer electronic devices.
 - A. In film, light causes chemical changes that are made permanent in the developing process.
 - B. In digital still cameras and video cameras, several kinds of electronic devices are used. The most common, especially in higher priced cameras, is the *charge-coupled device*, or CCD. This device contains many electronic “bins,” called *pixels* or *photosites*, the electronic equivalent of the depressions in an egg crate. A particular 4-megapixel camera, for example, contains an array of 2272 x 1704 pixels, or nearly 3.9 million pixels. Light energy dislodges electrons, which collect in the electronic “bins”—the brighter the light or longer the exposure, the

more electrons collect. The information is read out by transferring electrons down the rows of bins and, eventually, out of the device to produce electrical signals that are then stored in electronic memory or written to discs.

- C. *Holographic images* are made by shining laser light on an object and combining the reflected laser light with light straight from the laser. The result is an interference pattern, which is captured on film. Laser light shined through the film recreates actual patterns of light on its way from the object, giving a three-dimensional image that appears different when viewed at different angles. Eventually, we can expect holographic movies!

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 28, p. 551 to end; chapter 29, pp. 582–583.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 16, sections 1–2.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 36.

Questions to Consider:

1. A virtual image “isn’t really there.” Why, then, can you see a virtual image?
2. If you wear eyeglasses or contacts, take a look at your prescription and explain what the numbers mean.
3. A philosophical question: Do you really “see” the world around you, or do you only “see” the image that forms on your retina?

Lecture Five

Is Seeing Believing?

Scope: Nature has a variety of tricks for altering the path of light, some of which form images while others result in such beautiful optical phenomena as rainbows. On the cosmic scale, the Universe itself forms distorted images of distant objects when their light passes intense accumulations of matter, such as black holes or galaxy clusters. And some of our most important technologies—including the optical fibers that form the backbone of the Internet and other high-speed computer networks—use these optical “tricks” to guide light and the information it carries.

Outline

- I. A close look at the refraction of light emerging from a denser material, such as glass, into a less dense material, such as air, reveals a new phenomenon—*total internal reflection*. Here, light striking the interface between the two materials at a sufficiently oblique angle can no longer emerge as a refracted beam but is, instead, reflected completely back into the denser material.
 - A. Total internal reflection has a variety of technological applications.
 1. High-quality binoculars use total internal reflection in prisms, rather than mirrors, to “fold” the path of light and allow for a more compact device.
 2. Total internal reflection in a cube-shaped piece of glass returns an incident light beam in precisely the direction from which it came. For example, such “corner cube” reflectors left on the Moon more than 30 years ago still reflect laser beams from Earth. This allows measurement of the Earth-Moon distance to better than 1 inch, thus helping to test Einstein’s general relativity.
 3. Total internal reflection is what guides light as it proceeds down optical fibers. These thin fibers of purest, high-transparency glass carry far more information than copper wires and cables and are at the heart of modern high-speed information systems, including the Internet. Optical fibers also give doctors a way of exploring visually the interior of your body.
 - B. Total internal reflection in raindrops and atmospheric ice crystals is responsible for a variety of beautiful atmospheric optical phenomena.
 1. Rainbows form when light from the Sun undergoes total internal reflection in raindrops that are located opposite the direction to the Sun. The rainbow always forms an arc located at an angle of about 42 degrees from the line passing from the Sun to the observer. Everyone sees his or her own different rainbow! The lower the Sun

is in the sky, the more of the arc is seen; from high mountains or airplanes, one can sometimes see the rainbow as an entire circle. Pause for thought: What's wrong with artist Harry Fenn's painting *Niagara*? The painting depicts an impossibly wide scene, given that the full rainbow arc is 84 degrees (2×42 degrees) wide.

2. Although light enters and leaves raindrops at a range of angles, there is a concentration of reflected light at about 42 degrees, resulting in a bright band in the sky when viewed at this angle. Because different wavelengths of light (different colors) refract differently on entering the drop, the most intense light emerges at slightly different angles for different colors (42 degrees for red, 40 degrees for violet). That is why we see not just a bright band but a rainbow of colors. The different colors actually come from drops at different heights. Sometimes, we see secondary or even tertiary rainbows, larger than the arc of the primary rainbow. These result from multiple reflections in the raindrops.
3. Other atmospheric optical phenomena include rings around the Sun and Moon, resulting from ice crystals. Another is the *glory*, seen as a ring of color surrounding the shadow of a mountain peak or of an airplane as it flies above clouds.

II. A more fundamental optical phenomenon is the blue sky itself.

- A. A detailed look at light as an electromagnetic wave shows that small objects, such as atoms and molecules, absorb light energy and undergo vibrations, which in turn, result in their emitting light in all directions. This process happens more effectively for shorter wavelengths—that is, bluer light. Thus, sunlight entering Earth's atmosphere is "scattered" in all directions. This happens more for blue light; for this reason, when we look at the sky, we see primarily blue scattered light, and the sky looks blue.
- B. Near sunrise and sunset, sunlight has to pass through much more atmosphere to reach Earth's surface, and even green and yellow light are scattered. This leaves predominantly red light coming directly from the Sun, giving us the beautiful colors of sunrise and sunset.

III. Naturally occurring optical phenomena can also deceive by creating distorted images that may or may not correspond to real objects.

- A. *Mirages* result when variations in air temperature near the ground cause differing amounts of refraction at different heights. Sometimes, mirages bring actual images of distant scenes, but more common are the *highway mirages* that refract blue sky light, creating the appearance of wet patches on the road.
- B. *Gravitational lensing* is the bending of light by gravity. Gravitational lenses occur naturally in the Universe and provide distorted or even multiple images of distant objects. Astronomers use gravitational

lensing to learn about astrophysical objects and the structure of the Universe.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 28 through p. 551.

Going Deeper:

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 15, section 1.

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 35, especially section 4.

Questions to Consider:

1. Where is "the end of the rainbow"? Why isn't it the same place for everyone?
2. In the primary rainbow, red appears on top. In the secondary rainbow, the order of colors is reversed. Why might this be?
3. Is seeing believing? How does physics inform your answer to this question?

Lecture Six

Music to Your Ears

Scope: Sound is a “poor cousin” to light, playing a lesser role in the Universe at large. That’s because sound, unlike light, doesn’t propagate through empty space, but requires a material medium, such as air. And in most materials, sound is much slower than light. But hearing is an important sense in humans and other animals, enabling oral communication, detection of prey, and the beauty of music. Sound does have more cosmic applications, too, including sound waves that propagate through the Sun and Earth to reveal the interior structure of our star and our planet. Recently, cosmologists have begun to study evidence for sound waves that echoed throughout the dense early Universe, leaving telltale evidence about the earliest instants of creation. Finally, both audible and inaudible sound waves make possible a wide range of technologies, including medical instruments that noninvasively measure blood flow, image internal organs, and examine growing fetuses.

Outline

- I. Sound, like any other wave, is a propagating disturbance that carries energy but not matter.
 - A. In the case of sound, the disturbance is a change in the pressure and density of a medium. In the most common case of sound waves in air, the wave consists of alternating regions of dense, higher pressure air and rarefied, lower pressure air. In typical sound waves, these variations are minute; for ordinary speech, the air pressure in the sound waves varies by only 1 part in 10 million from its normal value.
 - B. The speed of sound waves is determined by the properties of the medium in which the waves propagate. For air under normal conditions, the sound speed is about 340 meters per second, or about 700 miles per hour, 1,000 feet per second, or 1/5 of a mile per second. That’s the reason for the “5-second” rule for determining the distance to a lightning strike.
 - C. Sound waves of all frequencies and wavelengths are possible, but the typical human ear can detect sounds only between about 20 and 20,000 cycles per second (20–20,000 hertz). Sound waves come in all amplitudes, too, and the ear can handle a wide range of amplitudes. From the threshold of hearing to the threshold of pain is a factor of about a trillion in sound intensity!
- II. Any process that causes vibrational pressure changes in air results in a sound wave.

- A. Stringed musical instruments, as well as the human voice, rely on stretched chords or strings to produce sound, which is then further modified by the rest of the instrument or the human trachea and mouth.
 1. A given string can produce only certain frequencies of sound, because only certain wavelengths can “fit” on the string. The resulting waves are called *standing waves*. Varying the tension, or the position of a finger on a violin string, changes the allowed standing waves and, thus, the note the instrument produces.
 2. In wind instruments, standing waves result from vibrations of the air column in a closed tube. Again, only certain wavelengths can “fit.” Changing the length of the air column (as in a trombone) or closing and opening holes in the column changes the allowed wavelengths and, hence, frequencies.
 3. Different allowed vibrations can coexist, and the result is a complex wave. The mix of different frequencies determines the unique sounds of different musical instruments, even when playing the same note. In two-dimensional instruments, such as drums, the resulting patterns can be very complex.
 4. The Sun provides a more cosmic example of standing sound waves. Only certain vibrational patterns “fit” inside the spherical Sun, and studying these vibrations allows astrophysicists to probe the interior of our star.
- B. The perceived pitch of a sound wave varies if the source of waves moves relative to you. This is the *Doppler effect*, and it occurs because successive waves from a moving source are emitted at different locations.
 1. The Doppler effect in sound enables several important medical diagnostic techniques. Passing sound waves through the blood vessels enables measurement of blood flow as the sound pitch changes when sound waves interact with moving blood cells. In echocardiography, the Doppler effect in high-frequency ultrasound reveals the motions of the heart muscle.
 2. The same phenomenon also occurs for light and other electromagnetic waves. Measuring the Doppler effect in light from distant galaxies tells us that the Universe is expanding. Measuring the Doppler effect in microwaves reflected from your moving car allows a radar-equipped police officer to determine your speed. And measuring the Doppler effect in light from the Sun lets astrophysicists “see” those sound waves in the Sun—even though the sound can’t propagate through the empty space between Sun and Earth.

III. Sound also exhibits the wave behaviors, including reflection, refraction, diffraction, and interference, that we saw in Lecture Three.

- A.** Reflection of sound is responsible for echoes and medical imaging techniques and is crucial in the design of concert halls.
1. Music sounds “fuller” if different sounds come to your ears from opposite directions—hence, stereo and surround-sound. In a concert hall, that means reflecting sound so more of it comes from the walls and less from the ceiling. At the same time, the sound shouldn’t be absorbed because that reduces its overall energy.
 2. Ultrasonic medical imaging uses the fact that waves reflect at an interface between two different materials to image structures in the body.
- B.** For any wave, the product of the wavelength and frequency gives the wave speed. Given that audible sound covers the frequency range from 20 to 20,000 cycles per second and the speed of sound is, roughly, 400 meters per second, the wavelength of sound waves ranges from about 20 meters (60 feet) for the lowest sound to 2 centimeters (about an inch) for the highest pitches. Diffraction of sound around normal-sized objects is, therefore, very different for sound of different pitches. That’s the reason, as noted in Lecture Three, that bass sound diffracts around corners, while higher notes don’t. It’s also why bats, whose insect prey are considerably smaller than an inch, must use ultrasound at frequencies above the range of the human ear.
- C.** Interference between sound waves of slightly different frequencies results in the phenomenon of *beats*, a slow variation in sound intensity resulting from interference that goes from constructive to destructive and back again. Beats form the basis of very sensitive frequency-measuring systems, and they enable airplane pilots to synchronize precisely the speeds of different engines.

IV. Faster than sound? Faster than light?

- A.** Yes and maybe. It’s possible to go faster than sound, but it’s hard work and produces *shock waves*, such as sonic booms, because the air ahead of you can’t “know” you’re coming.
- B.** It’s also possible to go faster than light can go in a material medium, and the result is the optical analog of a shock wave. But the nature of space and time rule out going faster than the speed of light in vacuum.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapters 20–21.

Going Deeper:

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 9, section 2.

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 17.

Questions to Consider:

1. Your neighbors are playing very loud music, yet you hear only the throbbing bass notes. Why?
2. As viewed from Earth, the light from distant galaxies is always shifted toward the red, and this shift increases with increasing distance to the galaxy. What does this say about the motion of distant galaxies relative to Earth?

Module Two: Going Places

Lecture Seven

May the Forces Be with You

Scope: Motion is the essential “happening” in our everyday physical world, as well as at the atomic and cosmic scales and everywhere in between. Cars whiz around a highway curve; CDs spin, and dancers twirl; molecules intertwine and separate, replicating our genetic structure; electrons flit about their atoms in a mysterious quantum dance; baseballs dip and curve; our planet Earth rotates daily while revolving yearly; whirling air congeals into the menacing motion of a tornado; frogs hop, snakes slither, and bumblebees lumber in improbable flight; 12,000 miles above Earth, a swarm of GPS satellites circles at 7,000 miles per hour to keep us informed of our exact positions; and galaxies hurtle away from each other, participants in the cosmic expansion. Understanding the universal drama in all these happenings means understanding motion.

Most of us are mired in an outmoded view of motion that dates to Aristotle, nearly 2,400 years ago. We believe that motion is somehow unusual, a state requiring explanation, and that you have to push things to keep them moving. Peculiar circumstances of life on our solid planet reinforce this and other misconceptions that follow from the Aristotelian viewpoint. But some 300 to 400 years ago, Galileo, followed by Newton, developed a better understanding of motion that is more consistent with the nature of physical reality. The Newtonian view culminates in Newton’s famous three laws of motion, which are introduced in this lecture and which provide the foundation for our exploration of motion throughout this module.

Outline

- I. Motion is ubiquitous! From the motion of an electron circling an atomic nucleus, to such everyday motion as walking or driving, to the stately motions of the galaxies—motion is what makes everything happen. Understanding motion is a big part of physics.
- II. Farewell to Aristotle.
 - A. The Aristotelian view holds that the natural state of objects, at least on Earth, is to be at rest. Motion requires a constant push or pull, and seeing an object in motion raises the question: “What’s keeping it moving?” Put more succinctly, *force*—the physics term for a push or pull—is what makes things move.

- B. In a “thought experiment,” Galileo suggested instead that uniform motion—motion in a straight line at unchanging speed—is a perfectly natural state requiring no explanation and no force. The *law of inertia* sums up this new understanding: If an object is at rest, it remains at rest, and if it’s in motion, then it keeps moving uniformly, in both cases, as long as no force acts on it. Inherent in the law of inertia is the notion that force is not the cause of motion but of *change* in motion.

III. Changing motion.

- A. Change in motion means *any* change—starting, stopping, a change in speed, and most often overlooked, a change in direction. A car going around a curve, even if its speed is constant, is nevertheless a car whose motion is changing. And, according to the law of inertia, that means a force (push or pull) must be acting on it.
- B. How much does motion change? That depends on how big the force is and how massive the object. This relationship is embodied in Newton’s famous *second law of motion*, written $F = ma$. Here, F is the force applied to an object whose mass is m , and a is the resulting acceleration of the object—meaning, the rate at which its motion changes. (Talk about a car going from 0 to 60 miles per hour in 10 seconds, and you’re describing its acceleration.)
 1. Newton’s second law says that for a given object, a larger force produces a larger acceleration, and if you apply the same force to two objects, the less massive one will have the larger acceleration.
 2. Newton’s *first law of motion* is the law of inertia, and it’s just the special case of the second law when there’s no force acting on an object. Then, the second law says there’s no acceleration—no change in motion—and that’s just the law of inertia.
- C. In what way does motion change? That depends on the direction of the force. Push an object in the direction it’s already going, and it goes faster but keeps going in the same direction. Push it exactly opposite the direction it’s going, and it slows down but keeps going in the same direction until it eventually reverses. Push it exactly at right angles to its motion, and its direction changes but not its speed. All these changes—speeding up, slowing down, changing direction—count as accelerations. Push an object at some arbitrary angle, and in general, its motion changes in both speed and direction.

IV. Action and reaction.

- A. Kick the bowling ball, and my foot hurts. I push against the wall, yet I don’t crash through it. For that matter, my weight pushes down on the floor, but I don’t fall downward. Why? Because in each case, whatever I push on automatically pushes back on me. The floor pushes up and supports me. The ball responds to my kick with a sudden large force

back on my toe. The wall pushes back, keeping me from falling forward. All these are examples of Newton's *third law of motion*.

- B. Newton's third law is often stated, "For every action there is an equal and opposite reaction." But this archaic language obscures the third law's simple meaning (and often leads people to apply the third law inappropriately to realms way beyond physics). What the third law says is this: If one object pushes on another, then the second object pushes back on the first with a force of the same strength. One push is the "action"; the other is the "equal and opposite reaction"—equal because it's the same strength and opposite because it pushes back, in the opposite direction. Put another way, forces always come in pairs.
- C. A classic example of Newton's third law is the rocket. The fact that gas rushes out the back of the rocket implies that the rocket itself must be exerting a force on the gas. Thus, the gas exerts a force on the rocket—and that's what accelerates the rocket forward. A detailed look shows that all the action is at the front end of the rocket, where gas molecules bouncing off the rocket chamber walls are what apply the force to the rocket. It's not, as the *New York Times* suggested in a famous 1920 editorial gaffe, that the rocket pushes against whatever is outside it.

V. If more than one force acts on an object, then the effect is the same as a single *net force* combining the strengths and directions of the various forces. The sensations you experience in an elevator provide a nice example.

- A. As the elevator starts up, you feel heavier than normal. That's because the elevator has to provide a greater force on you than the downward force of gravity in order to give you an upward acceleration.
- B. As the elevator moves upward or downward with constant speed, you're in uniform motion, so there's no net force on you. You feel normal.
- C. As the elevator slows at the top of its journey, your acceleration is in the downward direction. The force the elevator exerts is less than the force of gravity, to yield a net downward force. You feel lighter, and your stomach, obeying the law of inertia, seems to rise as it pushes upward on your internal parts.

VI. Energy in motion.

- A. Exerting a force on an object to make it go faster requires hard work and shows that a moving object has energy, called *kinetic energy*. That energy increases rapidly, quadrupling for every doubling of speed. That's one reason why driving at excessive speed is so dangerous.
- B. In contrast, exerting a force to keep an object in place, or to change its direction of motion but not its speed, requires no work—because the object's energy does not change.

VII. The scope of Newton's laws.

- A. Together, the second and third laws provide a full and consistent description of motion in the view of Newtonian physics. It's not that they're two independent statements that happen both to be true, but that they're intimately related requirements on how motion must occur. Without the third law, for example, a collision between two objects would produce an infinite acceleration, in violation of the second law.
- B. Newton's laws work well in describing the motion of everyday objects, but they break down at the atomic scale and for objects whose speeds relative to us approach the speed of light. In those realms, the laws of quantum physics and relativity, respectively, replace Newtonian physics. For most instances of "physics in your life," Newton's laws work just fine.
- C. Newton's laws are valid for anyone who is in a state of uniform motion. Anyone doing experiments on motion will discover or validate Newton's laws—as long as the experimenter is moving uniformly. You can be in a moving airplane, a cruise ship, at rest on Earth (which is only approximately in uniform motion), or in a high-speed spaceship moving uniformly, and Newton's laws will work the same way in all cases. This is a statement of the principle of Newtonian (also called Galilean) relativity, a first step toward Einstein's more inclusive relativity principle.
 - 1. Newton's laws *do not* apply in systems that aren't moving uniformly. You can't apply Newton's laws successfully to objects moving about in an airplane when the plane is accelerating down the runway, or when it encounters turbulence, or to objects in your car when it's rounding a curve.
 - 2. In all such cases, Newton's laws still ultimately describe the motions—but only when applied from the point of view of someone who is not participating in the acceleration. Much confusion results from trying to apply Newton's laws in situations where they don't apply!

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapters 2–5.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 5.

Questions to Consider:

- 1. The minute hand of an analog watch sweeps around the dial at a steady rate, making the complete circuit once each hour. Is the hand accelerating?

2. Does an object necessarily move in the direction of a force that's acting on it? If not, give some counterexamples.
3. Explain the feelings you have when an elevator starts and stops on its downward journey.

Lecture Eight

Aristotle's Revenge

Scope: If Newton's laws provide such an accurate description of motion, why do we cling to the Aristotelian view that motion is somehow unusual, that force is required to sustain motion, and that things move in the direction of the forces acting on them? Because here in our everyday lives on Earth, there's a hidden force that often obscures the simplicity of Newton's laws. That force is *friction*. Friction is not only a philosophical nuisance, obscuring Newton's vision, but it's a practical nuisance that can hinder our movements and prevent us from using energy efficiently. But it's also essential: Without friction, we couldn't walk, run, or dance; start, stop, or steer a car; or even balance on our two feet.

Outline

- I. Friction is a force that acts between two objects in contact, opposing their relative motion.
 - A. *Static friction* describes the frictional force between two objects that aren't, in fact, moving relative to each other. Up to a point, static friction can oppose any other force that's trying to set the surfaces in motion.
 - B. Once the maximum force of static friction is reached, the two objects move relative to each other. Then, the force of *sliding friction* (also called *kinetic friction*) acts to oppose the motion. To overcome this frictional force, we need to apply a constant force just to keep up a uniform motion. The fact that the frictional force isn't obvious reinforces the mistaken Aristotelian notion that it takes a force to keep an object moving. In fact, the net force on the object is zero when we take into account both the force we apply and the frictional force.
 - C. It takes less force to counter friction and keep an object moving than it does to overcome the friction acting on a stationary object. That means the force of static friction can exceed that of sliding friction.
 1. An important example is braking a car. The brakes, which themselves involve friction between two pads that clamp a spinning disc attached to the wheel, stop only the wheel—not, directly, the car. The force that stops the car is the force of friction between wheels and road.
 2. A wheel that's locked and skidding experiences sliding friction. But for a wheel that's rolling, the very bottom of the wheel is momentarily at rest relative to the ground; thus, it experiences the stronger force of static friction. That's why older drivers were

taught to pump their brakes in an emergency stop, rather than slamming them on; by keeping the wheels rolling, the pumping action results in greater friction and shorter stopping distances.

3. Most of today's cars have computer-controlled antilock brakes that sense when wheels are beginning to lock and automatically pump the brakes as needed to keep each individual wheel rolling. Drivers of such cars should slam on the brake in an emergency and let the antilock system handle the pumping. Antilock braking systems can significantly reduce stopping distances, and more important, they help maintain control by keeping all the wheels rolling.

D. Friction originates in forces between atoms in two surfaces in contact. Because all surfaces have some roughness, the area in actual contact is smaller than the surface area.

1. Pushing the surfaces more tightly together increases the contact area and, hence, the friction force. For that reason, the frictional force depends on another force acting perpendicular to the two surfaces.
2. When surfaces are at rest relative to each other, there's time for tighter bonds to form between them. It takes more force to break these bonds, and that's what makes the force of static friction greater.

II. Friction plays a major role in our everyday lives, working in conjunction with Newton's third law to help us move about.

- A.** In driving, friction not only stops our cars, but it also lets them start moving and keep moving in the face of opposing forces, such as air resistance. The engine turns the wheels, which push backward on the road. The third-law paired force from the road is what actually pushes the car forward.
- B.** Rounding a curve, a car's motion is changing, and Newton's second law says that there must be a force acting on it. That force is friction, again between tires and road. As always, that force acts in the direction of the *change* in motion, in this case, toward the center of curvature. On an icy road, there isn't enough friction, and you may not be able to negotiate the curve!
- C.** You couldn't walk without friction. In walking, the foot in contact with the ground pushes back against the ground. By Newton's third law, the ground pushes forward on the foot. That force, transmitted to the rest of the body through muscles and bones, is what propels you forward. It's easier when you lean forward a bit; think of a dancer or runner starting into motion. The same basic idea governs driving—especially starting and stopping. Imagine trying to walk or drive on frictionless ice!
- D.** Understanding friction and Newton's third law resolves the famous dilemma of the cart and horse: A horse pulls on a cart. But by Newton's

third law, the cart pulls back on the horse with an equal force. How can the horse/cart combination ever move?

1. The answer lies in looking at the *net* force on the horse/cart system. That force is the frictional force of the ground pushing forward on the horse's feet. That force results, via the third law, from the horse's pushing back on the ground. Because the two forces in this—and in any—third-law pair act on different objects, they don't cancel each other out.
2. In the case of the cart, the only force acting is the forward force from the horse. In the case of the horse, there are two forces acting: the forward force of friction from the ground and the backward force from the cart. They aren't a third-law pair, and they don't have to have the same magnitude. As long as the frictional force is greater, the horse and cart can move and, indeed, accelerate.

E. In some cases, friction is a nuisance. It acts to slow moving objects, and wastes energy by turning the useful energy of motion into useless heat. We use lubricating oils to provide a thin film that separates two surfaces, greatly reducing the friction. In some cases we want friction in one direction but not another. Waxes used on cross-country skis, for example, are engineered to exhibit high static friction but low sliding friction. That way, the skier can push back against the snow to get traction or to climb hills but experiences little friction when gliding forward. Rosin applied to violin strings or a dance floor exhibits the same properties.

III. *Fluid friction* arises when an object moves through a fluid, such as air or water. Here, collisions with the molecules in the fluid exert forces that oppose the object's motion. Left alone, an object moving through a fluid will eventually come to rest relative to the fluid; to keep it moving, another force must be applied.

- A.** The force of fluid friction increases rapidly with the object's speed. Highway speed limits were once capped at 55 miles per hour, a fuel-saving measure inspired by the energy shortages of the 1970s. At high speeds, air resistance is a major energy drain.
- B.** A falling object accelerates downward under the influence of gravity. But as it gains speed, the force of fluid friction increases. At some speed, that force equals the force of gravity. Then, there's no net force, so the object falls with constant speed—called the *terminal speed*. The force of gravity depends on the object's mass, but fluid friction depends on surface area. Parachutes take advantage of this relation, offering a large surface area to the air and, thus, making for a small terminal speed.

Suggested Reading:

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, section 1.4 through p. 57.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 6, sections 4 and 5.

Questions to Consider:

1. An ice skater does best on nearly frictionless ice, but walking would be almost impossible under those conditions. Why the difference?
2. How can a suction cup hold objects on a vertical wall?
3. An object rests on an incline, held in place by the force of friction. But if you give it the slightest push, it may begin to slide and keep sliding. Why doesn't it again stop?

Lecture Nine

Going in Circles

Scope: Motion in curved paths, especially circles, is important in everything from atoms to cars to satellites to galaxies. Yet few ideas in physics cause so much needless confusion—confusion that is unfortunately abetted by some of the terminology physicists use. Understanding circular motion is easy if you have faith in Newton and realize that any change in motion—including a change in direction—requires a force acting in the direction of that change. Grasping this simple point explains why highway curves are banked, how an airplane steers, and why you seem to weigh a little less at the equator. Newton's law applied to circular motion even explains the improbable sight of riders completely upside in a loop-the-loop roller coaster. And in the cosmic realm, the same ideas show why satellites, despite no rockets firing, nevertheless don't fall to Earth.

Outline

- I. Newton's second law says that any change in motion—whether a change in speed or in direction—requires a force.
 - A. Believe Newton and you recognize that motion in a circular path—a motion whose direction is continually changing—requires that there be a net force acting on the object.
 - B. Because force causes not motion but *change* in motion, the direction of the force is in the direction of the *change* in motion. In the case of circular motion, that direction is toward the center of the circle. For that reason, whatever force causes circular motion is sometimes called a *centripetal force*.
 1. That's *centripetal*, not *centrifugal*. "Centrifugal force" is a term that ought to be banned altogether! There's no such force! To talk about my whirling ball staying in its circular path because the "centrifugal force" balances the force of the string or the Moon staying in its orbit because a "centrifugal force" balances the force of gravity is to talk nonsense. When an object is in circular motion, it's accelerating—so the forces on it can't be balanced. There must, according to Newton, be a net force toward the center of its circular path. Eliminate that force and the object does not move outward, in the direction of some hypothetical "centrifugal force," but in a straight line in the direction it was moving when the force was removed. (The term "centrifugal force" is used to describe apparent but actually nonexistent forces one experiences in rotating frames of reference—a sort of fudge to make Newton's laws seem to apply

in a situation, namely an accelerating system, to which they don't, in fact, apply. In the hands of experts, the term can occasionally be useful, but it obscures the meaning of Newton's laws and is confusing to anyone trying to learn physics!

2. Even the term *centripetal* should be used with caution. It's easy to think there's some special, separate kind of force called a *centripetal force*. There isn't. *Centripetal force* is just the name given to any actual force that keeps an object moving in a circular path. It's always a real, identifiable force—whether the force of the string on my whirling ball, the friction between tires and road as a car rounds a curve, or the force of Earth's gravity acting to keep the Moon in its circular orbit. To say "centripetal force" is not to explain circular motion; you need to find a real, physical force that's acting.

- C. The faster one goes in a curved path, the shorter the time to get from one part of the curve to another and, therefore, the greater the rate of change of one's motion. Furthermore, a greater speed means a greater difference between one's motions at two different points on the curve. Together, those two facts mean that acceleration in circular motion increases rapidly with increasing speed—namely, as the *square* of the speed. But on a path of larger diameter, the time is longer and, therefore, the rate of change of motion is lower. As a result, the acceleration decreases with increasing path diameter—in fact, as the inverse of the diameter (or radius).

II. Recognizing the need for a center-directed force in any case of circular motion explains a number of otherwise puzzling phenomena.

- A. Why are highways banked, or sloped, on curves? The answer is that, when they are, the force that the road exerts on a car has a component inward, toward the center of the curve. The banking angle can be chosen so that, for a car moving at a specific speed, the force from the banked road is itself sufficient to hold the car in its curved path. Then there's no need for friction, no need to rely on the condition of the car's tires or a clear, dry road to ensure that the car can negotiate the curve.
1. Driving on a flat road, incidentally, you may find yourself "cutting the corner" and drifting into the other lane.
 2. You do that because you instinctively understand the physics of circular motion and recognize that a curve of larger diameter means less force is needed for your car to negotiate the curve. You feel less likely to lose control—although you're at risk by being in the wrong lane!
- B. Why does a bicyclist or ice skater lean when rounding a curve or a dancer when prancing around the stage in a curved path? For the same reason: The force that the road, ice, or stage exerts on the cyclist, skater, or dancer is in the direction of the tilt; thus, it includes both a

vertical component (that balances gravity; there's no acceleration in the vertical direction) and a horizontal component that maintains the curved path. That tilted force is transmitted up through the tilted body, giving each part of the body the right force to keep it moving in the curved path. The body naturally finds just the right tilt to make this happen.

1. Why doesn't the leaning cyclist fall over? This question is a good test of your faith in Newton's laws! Is the cyclist's acceleration consistent with the forces acting? Yes! Because gravity is balanced by an upward force from the road, there's no vertical acceleration. But there's an unbalanced horizontal force, so the cyclist is accelerating—the direction of motion is continually changing, making a curved path. The net force is doing just what Newton's law says it should, namely, providing an acceleration. There's no force "left over" to make the cyclist fall.
 2. For the cyclist on an unbanked road or a dancer on a stage, friction provides the horizontal force. Make the road or stage too slippery, and there won't be a large enough horizontal force. Then, the circular motion cannot be maintained, and the cyclist or dancer may start to fall over. In the case of the skater, the sharp skate blade digs into the ice and pushes horizontally. The ice pushes back, providing the force that keeps the skater in the circular path.
- C. Why does an airplane bank when turning? For the same reason: Normally, the upward force from the air on the wings is what keeps the plane aloft (more on this in the next lecture). But when the plane is tilted, the wing force has a horizontal component, and that's what keeps the plane turning. Although you know the plane is tilting because you look out the window and see either sky or ground, you don't feel the tilt. And objects on your seat-back tray don't go sliding in the direction of the tilt. Why not? Because the normally upward force of the seat on you now has a component in the horizontal direction, and that's just what's needed to keep you participating in the plane's circular path. It's the same for the airline peanuts spread on your seat-back tray.
- D. Why don't you fall out of a loop-the-loop roller coaster? Why doesn't the water fall out of the bucket as I whirl it over my head? Don't tell me it's held in place by "centrifugal force"—or even by any force. What forces do, Newton tells us, is to *change* motion. Gravity, even though it's a downward-pointing force, doesn't necessarily make things fall down. What it does is to *change* an object's motion toward a more downward direction.
1. For an object moving in a circular path, you've seen that there must be a force pointing in the direction toward the center of the path.
 2. If the circular path is oriented vertically, that direction is downward when the object is at the top of its circle.

3. If the object's speed is just right, then gravity will provide exactly that needed force. The force is causing the change in motion—in this case, motion in a circular path, and Newton's second law is satisfied. There's simply no reason to expect the object to "fall down." A force is causing an appropriate change in motion, and that's just what we Newtonians should expect.

4. If the object is moving even faster, then an additional force is needed to help gravity maintain the circular motion. For the roller coaster, that force is the track pushing down on the roller-coaster car; for the water, it's the bottom of the bucket pushing down; and if I whirl a tennis ball on a string in a vertical circle, the string is still exerting a downward force even at the top of the circle.

5. If the object is moving too slowly, so that the force of gravity is stronger than the force needed to maintain the circular path, then the object will "fall" out of its circular path.

E. Why do you "weigh" less at the equator? When you stand on a scale, you push down on it, and by Newton's third law, the scale pushes back up on you. The number the scale gives for your weight is actually the force that the scale is pushing up with. If you weren't accelerating, the net force on you would be zero, and the scale force would exactly balance the force of gravity. But at the equator (or anywhere but at the North or South Pole), you're in circular motion because Earth is rotating. There must be a net force toward the center of that circular path. At the equator, the center of your circular path is Earth's center, and the direction toward that center is downward. In order that there be a downward force on you, the force of gravity must be stronger than the scale force; thus, the scale reads less than it would at the pole (or elsewhere on Earth), and you "weigh" less. (Actually, you don't weigh less; weight is the force gravity exerts on you, and that stays the same. But your *apparent weight* changes.)

III. All these examples involve the simple fact of Newton's laws. In particular, changing motion requires a force. Motion in a circular path is changing motion, so there must be a force on any object moving in a circular path. Find that force and you'll understand the circular motion!

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 8, pp. 138–141.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 5, sections 5.1–5.2.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 6, section 6.3.

Questions to Consider:

1. Automobile racetracks are designed in such a way that the banking angle is slight at the inside edge of a turn but gets steeper as one moves outward. How does this make the track safer?
2. If you suspend a weight from a string at either of Earth's poles or at the equator, the string will hang straight downward—meaning toward the center of the Earth. But at any latitude other than equator or pole, it will not hang straight downward (although the deviation is too small to be obvious). Explain, in terms of Newton's laws. Note that the only two forces on the weight are those of the string and of gravity and that gravity pulls directly downward.

Lecture Ten

Taking Flight

Scope: Air travel provides our fastest means of “going places” on planet Earth. To fly, we must somehow overcome the force of gravity. The first flying machines were balloons, which fly for the same reason that boats float—namely, they weigh less than an equal volume of air. But most modern aviation takes its cue from birds and bats, which are heavier than air but nevertheless attain support from the air. As with all everyday motion, Newton’s laws again provide a simple but full explanation for the phenomenon of flight. A more sophisticated approach to flight comes from recasting the basic principles inherent in Newton’s laws in a way that is especially descriptive of fluid motion.

Outline

- I. Gravity is a force that acts between all objects in the Universe, but only with large accumulations of matter, such as planets and stars, is the force significant.
 - A. The force Earth’s gravity exerts on an object is proportional to the object’s mass. But because it takes a larger force to give the same acceleration to a larger object, all objects experience the same acceleration if the only force acting is gravity.
 - B. To keep an object from accelerating downward requires an upward force equal in strength to the downward force of gravity. In our everyday lives, that force comes from the ground, from the floor structures of buildings, from furniture we’re sitting or lying on, or from cables supporting elevators and bridges. For flying objects, the air itself provides the force that balances gravity.
- II. Lighter-than-air craft—hot-air and helium balloons—fly because they literally float in the air, for the same reason an object floating in water rises to the surface.
 - A. A fluid such as air or water exerts a pressure, in all directions, that depends on the weight of the fluid above it. This pressure results in forces on objects in the fluid. For example, the weight of the atmosphere is such that we at Earth’s surface experience a force of about 15 pounds on every square inch of our bodies. We don’t feel that crushing force because the interiors of our bodies are usually at the same pressure.
 - B. Going upward through a fluid, the amount of fluid above us diminishes and so does the pressure. That’s why a rapid change in altitude causes “popping” of the ears—because internal pressure hasn’t had a chance to

equalize, we feel a force as a result of the different pressure on either side of the eardrum. This decrease in pressure with height means that an extended body experiences more pressure on its lower end than on its upper end—giving a net upward force. This is the *buoyancy force*.

- C. Buoyancy isn’t the only force acting on an object in a fluid; there’s also the downward force of gravity.
 1. A blob of fluid itself just sits where it is, with no net force on it. Therefore, the strength of the upward buoyancy force must just equal that of the downward gravitational force.
 2. If the object is denser than the fluid, then the gravitational force is greater, and there’s a net downward force. Most everyday objects are much denser than air, so the buoyancy force in air is negligible—but it’s always there. In water, it’s less negligible, which is why you can carry a concrete anchor underwater when you would have trouble on land.
 3. If the object is less dense than the fluid, then the buoyancy force is greater, and there’s a net upward force.
 - D. In a liquid, whose density doesn’t vary much, a buoyant object rises to the surface and extends above the surface by just the right amount that the buoyancy force on the submerged part balances gravity.
 - E. Because the density of air decreases with height, a rising balloon eventually reaches an altitude where its density equals that of the surrounding air. It’s then in *neutral buoyancy* and will float at that altitude unless its density changes. In water, fish and submarines control their densities to maintain this same state of neutral buoyancy.
- III. Birds, bats, and airplanes are all much denser than air, so gravity overwhelms the buoyancy force. But through motion of their bodies, especially their wings, these objects produce enough force to stay aloft.
 - A. Winged flight is often explained in complex terms involving the flow of air past a carefully shaped wing structure. Indeed, full understanding of the subtleties of flight, as well as good aircraft design, requires such a description. But flight is, ultimately, governed by Newton’s laws, and those laws provide the simplest explanation.
 - B. Any heavier-than-air flier, whether bird, airplane, or helicopter, must exert a downward force on the air. By Newton’s third law, the air then exerts an upward force on the flying object. It’s that force, called *aerodynamic lift*, that counters gravity and keeps the flier aloft.
 1. A helicopter is perhaps easiest to understand. Its rotating blades act like a big fan, pushing air downward. By Newton’s third law, the air pushes back up on the blades, providing the lift force that supports the helicopter. The helicopter can hover in one spot because the moving blades, not the body of the craft, are what provide the lift.

2. The wings of an airplane perform the same function as the blades of a helicopter—ultimately, the plane’s motion causes the wings to exert a downward force on the air, and the result is an upward force from the air on the wings. Although the behavior of a wing is often depicted in terms of complicated airflows, the key to flight is that the wing deflects air downward.
 3. The curved path of the deflected air means the force acting on the air must be toward the center of the curve (as discussed in the previous lecture); thus, it points not straight downward, but downward and forward. Therefore, the force on the wing points upward and backward. These two different components are called *lift* and *drag*, respectively.
 4. In principle, one could fly with a flat board for a wing—provided it was tilted. Again, the point is to achieve a downward force on the air. This wing isn’t particularly efficient—the drag component is large—but it would work.
- C. The deflection of air by an airplane wing, helicopter blade, or bird’s wing necessarily results in a backward-directed drag force.
1. Because lift results from motion through the air, and because drag always accompanies lift, any heavier-than-air flier must exert a horizontal propulsion force to overcome the drag. In an airplane, that force comes from jet or propeller engines that ultimately push backward on the air, resulting in a forward push on the craft. In birds, the force comes from complex motion of the jointed wing.
 2. What about gliders? When a bird or glider is gliding, without propulsion, the drag force will eventually slow the glider and decrease the lift. Only with upwelling air currents can a glider stay aloft indefinitely.
 3. Good aircraft design seeks to minimize drag while maximizing drift. That’s where sophisticated wing shapes and detailed analysis of airflow become important.
- D. The simplest fluid-flow explanation of flight, and the most common explanation usually given, involves *Bernoulli’s principle*. This principle states that fluid pressure is high where flow speed is low and vice versa. This is not a wholly new principle of physics but a description, for fluids, of the interchange of energy between the kinetic energy of fluid motion and the energy associated with the random motion of particles that gives rise to fluid pressure.
1. Around a wing, whether a flat board or a carefully shaped airfoil, air flows more rapidly over the top surface of the wing, resulting in a lower pressure. As a result, there’s a net upward pressure force on the wing, and this is what provides the lift. But there’s no new physics here; this is just another way of describing Newton’s third-law force pairs that keep the wing aloft.

2. The lift force is perpendicular to the wing, so when an airplane banks, the lift force acquires a horizontal component. That’s what allows the plane to turn, as described in the preceding lecture.
 3. Bernoulli’s principle provides explanations for a variety of other everyday phenomena, from the flight of a curve ball thrown by a baseball pitcher to the forces on sail and keel that propel a sailboat.
- E. The atmosphere in which we live provides us with not only the oxygen we need to survive but also, through Newton’s laws, myriad ways for us to interact with the air. All of aviation, so vital to our modern world, is the result of one such interaction.

Suggested Reading:

Stephen Dalton, *The Miracle of Flight*, especially chapter 1.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 4, section 4.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 9.

Paul Hewitt, *Conceptual Physics*, chapter 14.

Elizabeth Wood, *Science from Your Airplane Window*.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 18.

Peter Wegener, *What Makes Airplanes Fly?*, chapters 1–9.

Questions to Consider:

1. Weighing an object on Earth’s surface, at the bottom of the atmosphere, does not give an exact measure of the gravitational force on the object. Why not? For what sorts of objects is the discrepancy greatest?
2. Descriptions of the physics of sailboats often speak of horizontal “lift forces.” What might that term mean in the context of airplane flight?
3. Air supports an airplane’s wings. What holds up the body of the airplane?

Lecture Eleven Into Space

Scope: Space flight is truly “physics in your life”—and not just for astronauts. Today, a host of space technologies are at work in communications, agriculture, resource exploration, surveying, navigation, and tracking everything from freight shipments to Alzheimer’s patients to lost pets. Newton was the first to understand the physics of space flight, some 300 years before humankind placed the first artificial satellites in orbit. Space technology now has many earthly applications, but it also allows us to explore the Universe beyond our planet, and the environment of an orbiting spacecraft provides a unique opportunity to study the behavior of materials and living things under conditions where gravity seems—but, in fact, is not—absent.

Outline

- I. Legend has it that Isaac Newton was sitting under an apple tree and was struck by a falling apple, causing him to discover gravity. Actually, Newton’s ingenious insight was the recognition that the motion of the apple and the motion of the moon are the same—both are attracted to Earth by a universal force of *gravity* that acts between any two objects in the Universe.
 - A. The force of gravity, according to Newton, depends on the product of the masses of the two objects. Only large masses, such as planets and stars, exert substantial gravitational forces.
 - B. The force of gravity decreases with distance between the objects, falling off as the inverse square of the distance. That distance is measured from the center of a spherical object like a planet or star.
- II. Gravity works like any other force, obeying Newton’s laws and, in particular, causing not motion itself but *change* in motion. The direction of that change is toward the gravitating object—Earth, Sun, or other massive body.
 - A. An object that’s initially at rest above Earth will fall straight down, accelerating as it goes.
 - B. An object that’s initially moving upward will have its motion changed in the downward direction. It will slow, come to an instantaneous stop, and move downward while gaining speed. All the while, even when it’s instantaneously stopped at the peak of its path, it’s accelerating downward because of the downward force of gravity.
 - C. An object that’s initially moving horizontally will have its motion altered in the downward direction—that is, it will describe a curved

path, deviating from the straight line it would have followed in the absence of gravity.

- D. Newton considered shooting objects horizontally off a high mountain. The faster an object goes, the farther it travels before hitting the ground. Give it just the right speed, and gravity pulls the object out of its straight-line path at just the rate that Earth is curving away beneath it. The object is then in a *circular orbit*. Absent air resistance or other nongravitational forces, it will continue forever in this path.
 1. What keeps an orbiting object from falling? Nothing! It is “falling,” in the sense that its motion is being changed in the direction toward Earth. It’s falling *toward* Earth but not *to* Earth. And that’s just what Newton’s second law says it should be doing. Gravity, like any other force, doesn’t *cause* motion; it *changes* motion. Gravity doesn’t necessarily make things fall to Earth, but it does make motion change in the earthward direction. It’s no different than the ball on the string; the string is pulling on the ball, causing its motion to deviate from a straight line in the direction of the string’s pull, but the ball doesn’t get any closer to the other end of the string.
 2. It takes no effort to remain in orbit; no rocket engines are firing, and there’s no need to supply any energy. Gravity alone provides the force that shapes the orbit, and the orbiting object’s energy remains constant.
 3. Orbits need not be circular; shoot the object a little faster or a little slower off Newton’s mountain, and it goes into an elliptical orbit. Newton invented calculus to work out the math associated with gravity and showed that orbits are, generally, elliptical. The Earth or other gravitating body is at one focus of the ellipse. Here, I’ll consider only circular orbits.
- E. Lacking mountains that stick up out of Earth’s atmosphere, we achieve circular orbits by launching spacecraft with rockets that take them above the atmosphere. At the desired altitude, rocket engines give the spacecraft just the right speed for a circular orbit at that altitude.
 1. We have no choice in that speed; it’s determined entirely by the altitude and the mass of the Earth. For so-called *low-Earth orbit*, where the distance from Earth’s surface is far less than Earth’s radius, the gravitational force on an object is nearly the same as at the surface. In this case, the speed needed for circular orbit is about 17,000 miles per hour, and the resulting time to complete a full orbit is about 90 minutes. The International Space Station, space shuttles, and a host of other satellites are in low-Earth orbit.
 2. *Equatorial orbits* put satellites on paths above and parallel to the equator. They remain always above the equator. Equatorial orbits require the least energy, because a satellite can be launched

eastward from low latitudes, taking with it the great speed associated with Earth's rotation near the equator. This is why most launches take place from low latitudes and in an eastward direction.

3. *Polar orbits* take satellites over the poles. As Earth rotates beneath a polar-orbit satellite, the satellite passes over every point on the planet. Orbits between polar and equatorial cover all points between the highest north and south latitudes reached in the orbit.
4. At higher altitudes, the strength of the gravitational force begins to drop appreciably. The speed needed for a circular orbit decreases, and the orbital period increases. The Moon is so far away that its orbital period is 27 days.
5. Somewhere between the 90 minutes of near-Earth orbit and the 27-day lunar orbit, there must be an altitude where the period is 24 hours. It's easy to calculate that this occurs some 22,000 miles above Earth's surface. "Park" a spacecraft above the equator at this altitude, and it will appear at a fixed point in the sky because its orbital period exactly matches Earth's daily rotation. This *geosynchronous orbit* is valuable space real estate, and it's already getting crowded with communications satellites. Satellite TV dishes are all aimed at geosynchronous satellites suspended 22,000 miles over the equator.

F. Orbits involving more than two bodies present a formidable mathematical challenge, although some special cases can be solved easily.

1. An interesting place in space is the so-called *Lagrangian point, L1*. Located about a million miles sunward of Earth, this is a point where the oppositely pointing gravitational forces of Sun and Earth combine to give an orbital period of exactly one year for a circular orbit. Thus, a spacecraft in the vicinity of L1 remains always on the Sun-Earth line, about 1 percent closer to the Sun than Earth.
2. Spacecraft that observe the Sun and monitor emanations from it are often placed at L1 because their view of the Sun is never blocked by Earth.

G. Maneuvering in space can be counterintuitive.

1. With circular orbits, the higher the orbit the more energy required. But higher orbits are slower—so to go slower, one has to speed up! And to speed up, one has to slow down and drop into a lower orbit. Overtaking another spacecraft in the same orbit illustrates this strange state of affairs.
2. Interplanetary space travel requires more elaborate maneuvers; more on this in the next lecture.

III. The environment in an orbiting spacecraft is often termed "zero gravity" or "microgravity," while astronauts and everything else on the spacecraft are said to be "weightless." This "weightlessness" makes an orbiting spacecraft

an excellent place to study biological and industrial processes, including the growth and development of new materials.

- A. *Weight* means the force that gravity exerts on an object. Given that the gravitational force is what keeps a spacecraft and its contents in orbit, objects in space cannot be weightless! If they were, they would move off in a straight line, as required by Newton's first law in the absence of forces.
- B. However, objects in an orbiting spacecraft *seem* weightless. There's a simple reason for this. As shown in the previous lecture, the combination of Newton's law of gravity (force of gravity is proportional to an object's mass) and Newton's second law of motion (force needed to accelerate an object is proportional to the object's mass) results in all objects experiencing the same acceleration as a result of gravity.
 1. Imagine you're in a falling elevator, plummeting downward under the influence of gravity alone. You drop some objects. Because they, too, share your downward acceleration, they don't move relative to you. Relative to you, in your downward-accelerating elevator, these objects seem weightless. So do you, relative to the elevator.
 2. It doesn't matter whether the elevator is falling vertically or has some sideways motion as well—all objects in it share the same gravitational acceleration and, thus, relative to each other and the elevator, they seem weightless.
 3. Falling elevators eventually hit the ground, with disastrous results as nongravitational forces act. But an orbiting spacecraft is just as much a "falling" object, moving under the influence of gravity alone. It, and everything in it, share the same acceleration and, therefore, seem weightless in the environment of the spacecraft. It's this *apparent weightlessness* that is incorrectly referred to as "zero gravity" or "weightlessness."
 4. Apparent weightlessness has, in principle, nothing to do with being in outer space. "There's no gravity in space, and that's why things are weightless" is a common misconception. Apparent weightlessness arises any time the only force acting on an object is gravity. That condition is called *free fall*. Within Earth's atmosphere, air resistance provides an additional force, making true free fall hard to achieve. But we can mimic it, as is done in NASA's "Vomit Comet" aircraft, by flying on trajectories identical to those that an object would follow in the absence of air resistance. Weightless scenes in the film *Apollo 13* were filmed in this way.

Suggested Reading:

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 5, sections 4–5.

Paul Hewitt, *Conceptual Physics*, chapters 9 and 10.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff. *Physics for Scientists and Engineers*, chapter 9.

Questions to Consider:

1. A popular children's book once explained weightlessness by saying, "There's no gravity in space." Criticize this statement.
2. Jules Verne's 1865 novel *From the Earth to the Moon* imagined a lunar journey in a capsule shot from a giant cannon. Verne realized there would be a point on the trip where the gravitational forces from the Earth and Moon would exactly cancel, and he thought his astronauts would seem weightless at that point only. Why was he not correct?
3. Name some ways in which space technology affects your everyday life.

Lecture Twelve

A Conservative Streak

Scope: All the motions we've discussed in this module follow ultimately from Newton's three laws and an understanding of the forces that act on objects. But sometimes we can gain more insight into motion by following quantities whose values, under the right circumstances, stay unchanged. We call these *conserved* quantities. Two particularly important conserved quantities are *energy* and *momentum*. Invoking the conservation of energy and momentum explains many of the interactions that occur among objects in everyday life, as well as in the atomic and cosmic realms. Combined with Newton's laws, conservation principles also show us how to describe the motions of composite objects—including the human body—in simple but sometimes surprising ways.

Outline

- I. We have an intuitive feel for the term *energy* as we talk about someone's "personal energy," describe a dance performance as having "high energy," or recognize that a volcanic eruption releases a lot of "energy." Energy is one of the two basic "substances"—the more familiar is matter—that make up the Universe.
 - A. An aside: Energy and matter are really two sides of the same coin, as Einstein recognized in his famous equation $E = mc^2$. But that's a topic for The Teaching Company's course *Einstein's Relativity and the Quantum Revolution*.
 - B. Energy comes in many forms. Here, we're concerned with only two of these forms; later lectures will expand the concept of energy to new forms.
 1. *Kinetic energy* is the energy associated with the motion of macroscopic objects, such as baseballs, cars, people, planets, stars, and galaxies.
 2. *Potential energy* is "stored energy," associated with the configuration of objects or systems of objects. For example, a bowling ball sitting on the table has higher *gravitational potential energy* than when it's sitting on the floor. A stretched spring, rubber band, or bungee cord has more *elastic potential energy* than when it's unstretched.
 - C. When we (or any other agent or body) exert a force on an object as it moves through some distance, we do *work* on the object and supply it with energy.

1. Lifting the bowling ball from the floor, I apply a force to it, and I do work. In this case, the work ends up as gravitational potential energy.
 2. Pushing the bowling ball along the table, I don't change its height, so I don't add gravitational potential energy. Instead, I make it go faster, thus increasing its kinetic energy.
- D. A force such as gravity or the force in a spring is said to be *conservative* because any work done against the force gets stored as potential energy. The system can "give back" this stored energy as kinetic energy.
1. When we're dealing with conservative forces, the total energy stays the same—it's *conserved*. Energy may change from kinetic to potential and back, but the total energy remains the same.
 2. Examples include a pendulum, a mass vibrating back and forth on a spring, and a satellite in an elliptical orbit.
- II. In formulating his laws, Newton was concerned with finding some measure of what he called the "quantity of motion." He hit on the product of an object's mass with its velocity—the latter being a description of both speed and direction. This product is called *momentum*, and Newton's second law can be understood as saying that forces cause changes in momentum, with the rate of change of momentum being equal to the force. The familiar equation $F = ma$ is a special case of this more general statement.
- A. Momentum is a particularly interesting concept when applied to systems consisting of more than one object, such as the human body, an exploding firecracker, a pair of colliding vehicles, partners in a dance, or all the balls on a pool table.
1. Individual components of a system may exert forces on each other, as in the pressure forces driving an exploding firecracker apart, the force that muscles exert on an arm or a leg, or the force one car exerts when it strikes another. But Newton's third law states that forces come in pairs; thus, if part A of a system exerts a force on part B, then B exerts an equal but opposite force back on A.
 2. These paired forces between components of a composite system are *internal* to the system. Although they can change the motion of individual components, because they cancel in pairs, these internal forces exert no net force on the system as a whole.
 3. As a result, the overall momentum of a composite system can't change unless there's a net force acting from outside the system. Under those conditions, we say that the system's momentum is conserved. Momentum conservation often provides a "shortcut" to understanding interactions where we can't or don't want to get into the details of the forces.

- B. Even if there are external forces, they affect only the composite object's *center of mass*, a point that acts as though all the mass is concentrated there.
1. That pair of rollerbladers seen on the video clip had no external force acting on them. Their center of mass remained right where it was—in between them—even as they moved apart.
 2. A ball or other simple object tossed into the air describes a parabolic trajectory under the influence of gravity. A rigid, extended object may undergo much more complicated motion, but its center of mass still describes a simple parabolic path.
 3. Flexible objects, including the human body, can change the relative location of the center of mass. Raise your arms and legs, for example, and your center of mass rises in your body. Dancers, acrobats, jumpers, and divers exploit this possibility to give illusions of motion that seem to violate the laws of physics.
- III. The conservation laws for momentum and energy combine to provide a powerful way of describing *collisions*—short, intense interactions between two objects. Examples include a baseball and bat, a pair of subatomic particles in an "atom smasher," an automobile collision, a spacecraft's close encounter with a planet, and even two colliding galaxies.
- A. *Intense* means an interaction in which the forces between the colliding objects are vastly greater than any external forces acting on both. In that case, we can neglect the external forces and treat the colliding objects as a single system whose total momentum does not change during the collision.
- B. If the forces between the colliding objects are conservative, then the total energy doesn't change either. Initially, the objects have only kinetic energy, which is stored temporarily as potential energy of the deformed objects during the collision, then released as kinetic energy. Such a collision is *elastic*.
- C. If the forces between the colliding objects are not conservative, some energy is lost as heat or permanent deformation—as in an automobile collision—and total energy is not conserved.
- D. What happens in a collision depends on the relative masses of the colliding objects. The different possibilities have significant implications for such varied applications as nuclear reactor design, sports equipment, and space flight. For elastic, head-on collisions with one object initially at rest:
1. If a massive object hits a less massive one, the massive one continues on, slowed slightly. The less massive object acquires a substantial velocity, but little of the total energy is transferred to it.

2. If a less massive object hits a more massive one, the less massive one rebounds. The more massive object acquires a slight velocity, but again, little of the total energy is transferred to it.
 3. If the objects have the same mass, the one that's initially moving comes to a complete stop and transfers all its energy to the other.
- E. An unusual example of a collision is the interaction of a spacecraft with a planet, a maneuver widely used in getting spacecraft to the outer planets and beyond. Here the "collision" is the close gravitational interaction between spacecraft and planet.
1. If the planet weren't moving, the spacecraft would swing around the planet and head out at the same speed but in a different direction.
 2. But because the planet is moving in its orbit around the Sun, the spacecraft rebounds with a higher speed than it had on approach. It has extracted energy from the planet's motion, and the latter, therefore, slows down—although imperceptibly, given the planet's huge mass.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapters 6 and 7.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapters 10 and 11.

Kenneth Laws, *Physics and the Art of Dance*.

Angelo Armenti, ed., *Physics of Sports*.

Questions to Consider:

1. If energy is conserved, why do we worry about trying to reduce our energy consumption—sometimes even called "conserving energy"?
2. A rocket operates by burning fuel that it already has on board and sending the exhaust out the back. Explain the operation of a rocket in terms of momentum conservation.

Glossary

Aerodynamic lift: The upward force of air on an airplane or bird wing.

Ampere: The unit of electric current, equal to 1 coulomb of charge per second.

Amplifier: An electronic circuit that boosts either the voltage or current of an electrical signal.

Amplitude: The size of the disturbance that constitutes a wave.

AND: The logical operation whose output is 1 only if both inputs are 1.

Angular momentum: A measure of an object's rotational motion; the product of rotational inertia and angular velocity.

Angular velocity: A measure of the rotation rate of a rotating object.

Antenna: A system of electrical conductors used to send or receive electromagnetic waves.

Apparent weight: The "weight" read by a spring scale, which may or may not be your actual weight (the force that gravity exerts on you), depending on whether or not you're accelerating.

Apparent weightlessness: The condition encountered in any freely falling reference frame, such as an orbiting spacecraft, in which all objects have the same acceleration and, thus, seem weightless relative to their local environment.

Arteriosclerosis: A buildup of fatty plaque in the walls of arteries. Can lead to blockage or to collapse, as described by Bernoulli's principle.

Atomic number: The total number of protons in an atom's nucleus and, hence, the number of electrons in a neutral atom. Determines what element an atom belongs to.

Axons: Long extensions of neurons that carry signals to other neurons.

Battery: A device that converts chemical energy to electrical energy by separating positive and negative charge.

Beats: Sound heard at the frequency difference between two sound waves of very similar but not identical frequency.

Bernoulli's principle: A statement of energy conservation in a fluid, showing that the pressure is lowest where the flow speed is greatest and vice versa.

Big Bang: The explosive event that began the Universe as we know it.

Bit: A single binary digit, which can have only one of the two values 0 or 1.

Buoyancy force: The upward force on an object that is less dense than the surrounding fluid, resulting from greater pressure at the bottom of the object.

Byte: A sequence of 8 bits.

Cache: Special high-speed computer memory used for temporary storage of data and instructions.

Carnot engine: A simple engine that extracts energy from a hot medium and produces useful work. Its efficiency, which is less than 100 percent, is the highest possible for any heat engine.

CCD: See **charge-coupled device**.

Center of mass: A point where an object acts as though all its mass were concentrated.

Central processing unit (CPU): The main electronic circuitry of a computer, which performs fundamental operations on digital data.

Centrifugal force: There's no such thing! Banish this word from your vocabulary. See Lecture Nine.

Centripetal force: Any real, physical force that acts to keep an object moving in a circular path. Examples include gravity for the Moon and the friction of tires on the road for a car rounding a curve.

Charge-coupled device (CCD): A light detector that captures visual information using electrons in individual picture elements (pixels). Used in digital cameras and many other devices.

Chip: See **integrated circuit**.

Circular orbit: One of many possible paths for an orbiting object; in a circular orbit, the object remains at a fixed distance from the gravitating center and its speed remains constant.

Classical physics: The theories and descriptions of physical reality developed before about the year 1900, specifically excluding relativity and quantum physics.

Clock: A circuit inside a computer that generates a periodic signal used for synchronizing and timing all computer operations.

Cogeneration: The process of generating both usable thermal energy and electrical energy in the same power plant.

Collision: An intense interaction between objects that lasts a short time and involves very large forces.

Compression: A technique used to reduce the number of bits needed to store digital information.

Conduction: Heat transfer by physical contact.

Conductor: A material that contains electric charges that are free to move and can, thus, carry electric current.

Conservation-of-energy principle: The principle that energy cannot be created or destroyed, strictly valid in pre-relativity physics.

Conserved quantity: A quantity whose value does not change, at least in a given circumstance.

Constructive interference: See **interference**.

Convection: Heat transfer resulting from fluid motion.

Convection oven: An oven that uses forced circulation of hot air to reduce cooking time.

Cosmic microwave background: Electromagnetic radiation in the microwave region of the spectrum, which pervades the Universe and represents a "fossil" relic of the time when atoms first formed, about half a million years after the Big Bang.

Cosmological constant: A quantity first introduced by Einstein into his equations of general relativity to provide a kind of antigravity effect that would keep the Universe static; later discredited. Recently revived as a possible explanation for the 1998 discovery that the expansion of the Universe is accelerating.

Coulomb: The unit of electric charge.

CPU: See **central processing unit**.

Critical mass: The mass of fissile material (uranium, plutonium) needed for a self-sustaining nuclear chain reaction.

Curve of binding energy: A graph describing the energy release possible in forming atomic nuclei; shows that both fusion of light nuclei and fission of heavy nuclei can release energy.

Data bus: Channel for high-speed data transfer among different components of a computer.

Depletion region: The region surrounding a PN junction, in which there is a dearth of free charges.

Destructive interference: See **interference**.

Differential GPS: Use of two Global Positioning System receivers to reduce timing and atmospheric errors.

Diffraction: The phenomenon whereby waves change direction as they go around objects.

Diffraction limit: A fundamental limitation posed by the wave nature of light, whereby it is impossible to image an object whose size is smaller than the wavelength of the light being used to observe it.

Diffuse reflection: The reflection of waves, especially light, from a rough surface. The light is scattered at different angles and does not form an image.

Diffusion: The process where a material or type of particle moves from regions of higher concentration to regions of lower concentration.

Digital information storage: The encoding and storage of information as a sequence of digital 0s and 1s.

Diode: An electronic device using a PN junction to restrict the flow of electric current to one direction only.

Doped semiconductor: A semiconductor to which impurities have been added to alter the material's electrical conductivity.

Doppler effect: The increase in perceived frequency (higher pitch for sound, bluer color for light) of waves when the source approaches the observer. Also, the decrease in frequency when the source recedes from the observer.

Drag: The backward-pointing aerodynamic force that resists the forward motion of an airplane, bird, or other heavier-than-air flying object.

Dynamic memory: Memory that stores information as electric charge. Must be refreshed several thousand times per second.

Elastic collision: A collision in which energy is conserved.

Electric charge: A fundamental property of matter that determines electric and magnetic interactions.

Electric current: A net flow of electric charge.

Electric field: The influence that surrounds an electric charge, resulting in forces on other charges.

Electric generator: A device that uses electromagnetic induction to convert mechanical energy to electrical energy. Typically, a generator involves a coil of wire rotating in a magnetic field.

Electromagnet: A magnet made by passing electric current through a coil of wire.

Electromagnetic induction: A fundamental phenomenon wherein a changing magnetic field produces an electric field.

Electromagnetic spectrum: The range of electromagnetic waves, organized by frequency or wavelength.

Electromagnetic wave: A structure consisting of electric and magnetic fields, each produced from the change in the other, that propagates through space carrying energy. Light is an electromagnetic wave. In vacuum, all electromagnetic waves travel at exactly the speed of light.

Electromagnetism: The branch of physics dealing with electricity and magnetism, described by Maxwell's equations as developed in the mid-19th century.

Electromechanical relay: A device using an electromagnetically actuated switch to allow one electric circuit to control another.

Electrostatic precipitator: A device that uses electric fields to remove particulate matter from smokestacks.

Energy: One of the two basic "things" that makes up the Universe. Energy is what makes everything happen.

Energy gap: The range of unavailable energies that separates two bands of allowed energy levels in a semiconductor.

Entropy: A measure of disorder. The second law of thermodynamics states that the entropy of a closed system can never decrease.

Equatorial orbit: An orbit that remains above Earth's equator.

Exclusive OR: The logical operation whose output is 1 if either, but not both, of its inputs is 1.

Extrinsic semiconductor: See **doped semiconductor**.

Faraday's law: The mathematical statement describing electromagnetic induction.

FET: See **field-effect transistor**.

Field-effect transistor (FET): A transistor in which an electric field exercises the control function.

First law of thermodynamics: The statement that energy is conserved, expanded to include thermal energy.

Flip-flop: An electronic circuit that has only two possible states. Used as the fundamental unit in static semiconductor memory.

Fluid friction: A friction-like force that slows the flow of a fluid, especially near a solid boundary.

Free fall: The state of motion of an object on which the only force acting is gravity. The object need not be moving downward!

Frequency: The number of complete wave cycles per unit of time; inverse of the wave period.

Friction: A force that acts between two surfaces, opposing any relative motion between them.

Fuel cell: A device that combines two chemicals (typically, hydrogen and oxygen), producing electric current in the process.

Fusion: A nuclear reaction in which light nuclei join to produce a heavier nucleus, releasing energy in the process.

Gate: The controlling electrode of a field-effect transistor; an unrelated definition is a circuit that performs a basic logic function.

General relativity: Einstein's 1915 theory that describes gravity as the curvature of spacetime.

Geosynchronous orbit: An equatorial orbit at an altitude of about 22,000 miles, where the orbital period is 24 hours. A satellite in such an orbit remains fixed over a point on the equator.

Gigabyte: A measure of computer memory, equal to about a billion bytes (exact value 2^{30} , or 1,073,741,824 bytes).

Gravitational lensing: The bending of light by the gravity of massive astrophysical objects.

Gravity: A universal attractive force that acts between all objects in the Universe.

Greenhouse effect: The trapping of outgoing infrared radiation by certain atmospheric gases, resulting in the warming of a planet.

Greenhouse gas: A gas that absorbs infrared radiation, thus contributing to the greenhouse effect.

Ground-fault interrupter: A safety device that senses imbalance in current on two wires, then shuts off the circuit to prevent electric shock.

Gyroscope: A rapidly spinning object whose rotation axis tends to maintain a fixed orientation.

Habitable zone: The region around a star where conditions are appropriate for life as we know it.

Half-life: The time it takes for half of the atoms in a sample of radioactive material to decay.

Heat capacity: A measure of the energy required to change an object's temperature.

Heat pump: A refrigerator run in reverse, pumping heat from the cooler outdoor environment into a building.

Hole: A place in a semiconductor where an electron is missing from the crystal structure. Acts as a positive charge.

Holographic image: A three-dimensional image made by recording interference patterns of wave fronts coming from the object being imaged.

Hyperfine transition: A transition between two very closely spaced atomic energy levels.

Induced electric field: An electric field produced not by electric charge but by a changing magnetic field.

Insulator: A material with no or few free electric charges and, thus, a poor carrier of electric current.

Integrated circuit: A circuit built on a single piece of silicon.

Interference: The process whereby two waves, occupying the same place at the same time, simply add to produce a composite disturbance. Interference may be constructive, in which the two waves reinforce to produce an enhanced composite wave, or destructive, in which case the composite wave is diminished.

Internal energy: The energy associated with random molecular motion; commonly but mistakenly called "heat."

Intrinsic semiconductor: A semiconductor made from a pure material.

Ion: An atom that has lost or gained an electron, thus possessing an electric charge.

Ionosphere: A region of Earth's atmosphere, beginning about 50 miles up, that contains free electrons and is, therefore, electrically conductive; affects the timing of GPS signals.

Kinetic energy: The energy associated with an object's motion.

Lagrangian point, L1: A point roughly 1 million miles sunward of Earth, where a spacecraft's orbital period is 1 year, allowing it to stay on the line between Earth and Sun.

Laser: A device that produces light or other electromagnetic radiation through stimulated emission; stands for *Light Amplification by Stimulated Emission of Radiation*.

Laser angioplasty: The use of laser beams to clear clogged arteries by vaporizing plaque.

Latent heat: Energy associated with a substance's being in a state requiring higher energy, as in the latent heat of water vapor, which can be released when the water condenses.

Law of inertia: The statement that a body in motion (or at rest) remains in uniform motion (or at rest) unless a force acts on it.

LCD: See **liquid-crystal display**.

LED: See **light-emitting diode**.

Lens: A piece of transparent material shaped so that refraction brings light rays to a focus.

Lift: See **aerodynamic lift**.

Light-emitting diode (LED): A diode engineered to produce visible or near-visible light when current flows across its PN junction.

Liquid-crystal display (LCD): A visual display device that uses electric fields to reorient the molecules of a liquid crystal, thereby altering the polarization of light.

Low-Earth orbit: An orbit whose altitude above Earth's surface is a small fraction of Earth's radius. The period of low-Earth orbits is about 90 minutes.

Magnetic field: The influence surrounding a moving electric charge (and, thus, a magnet) that results in forces on other moving charges (and on magnets or magnetic materials).

Magnetic resonance imaging (MRI): A procedure that uses spinning protons in a magnetic field to form images of the body's interior.

Magnetron: A special vacuum tube in which electrons undergo circular motion, producing microwaves.

Maxwell's equations: A set of four equations that describe all electromagnetic phenomena of classical physics.

Mechanics: The study of motion.

Megabyte: A measure of computer memory, equal to about a million bytes (exact value 2^{20} , or 1,048,576 bytes).

Memory: An electronic circuit that maintains a given state until the state is explicitly changed.

Metal-oxide-semiconductor field-effect transistor (MOSFET): A type of transistor widely used in computer circuits.

Microprocessor: The single-chip CPU of personal and other small computers.

Minority charge carriers: The free charges that are in a minority in a given semiconductor (electrons in P type, holes in N type).

Mirage: An image formed by refraction because of temperature gradients in the air.

Moderator: In a nuclear reactor, a substance that slows neutrons to make them more effective at causing fission.

Modern physics: The theories and descriptions of physical reality developed after about the year 1900, including specifically, relativity and quantum physics.

Momentum: A quantity that describes the "amount of motion" in a moving object, accounting for both velocity and mass.

Moore's law: The statement that the number of transistors per integrated circuit grows exponentially, doubling every year or two. Moore's law has held since the 1960s.

MOSFET: See **metal-oxide-semiconductor field-effect transistor**.

Motherboard: A circuit board holding the CPU, memory, and other components central to the operation of a computer.

MRI: See **magnetic resonance imaging**.

NAND: NOT AND; the logical operation whose output is the opposite of AND.

Natural greenhouse effect: The effect of natural greenhouse gases, particularly water vapor and carbon dioxide, in raising Earth's temperature some 60° F above what it would otherwise be.

Negative charge: The type of electric charge on the electron.

Net force: The sum of all forces acting on an object.

Neurons: Specialized cells that transmit electrochemical signals in the brain and nervous system.

Neutral buoyancy: The state of neither rising nor sinking that occurs for an object of the same density as the surrounding fluid.

Neutron: An electrically neutral component of the atomic nucleus.

Neutron activation: A process of inducing artificial radioactivity by bombarding substances with neutrons; the subsequent radioactive decay is used to identify the substances.

Newton's first law of motion: This is the same as the law of inertia.

Newton's second law of motion: The statement that an object's acceleration is proportional to the net force applied to it and inversely proportional to its mass.

Newton's third law of motion: The statement that forces always come in pairs; if one object exerts a force on a second object, the second exerts an equal but opposite force back on the first.

Nonthermal energy transfer: Energy transfer that does not rely on a temperature difference, as in a microwave oven.

Nonvolatile memory: Memory that retains information even when the power is off, as in a digital camera.

NOR: NOT OR; the logical operation whose output is the opposite of OR.

NOT: The logical operation whose output is the opposite of its input.

N-type semiconductor: A semiconductor doped so that the dominant free charges are negative electrons.

Nuclear chain reaction: An ongoing reaction in which neutrons released in nuclear fission go on to cause additional fission events.

Nuclear force: The force that binds protons and neutrons to form atomic nuclei.

Nuclear magnetic resonance (NMR): The process at the heart of MRI, whereby protons absorb radio waves of just the right frequency to set them precessing in a magnetic field.

Nuclear medicine: The use of radioactive substances to image body structures and analyze physiological processes.

Nucleosynthesis: The process of forming atomic nuclei, especially in stars and in the early Universe.

Ohm's law: The statement, valid for some materials, that the electric current is proportional to the applied voltage and inversely proportional to the material's resistance.

Optical storage medium: A medium, such as the CD or DVD, that encodes information in ways that can be read using light.

Optics: The branch of physics dealing with light and its behavior.

OR: The logical operation whose output is 1 if either or both inputs are 1.

Pacemaker: A specialized group of cells that provides the signal to govern the rhythmic beating of the heart.

Parallel communications: Data transfer that moves many bits simultaneously on separate wires.

Period: The time interval between two successive wave crests; equivalently, the time for a complete wave cycle.

PET: See **positron emission tomography**.

Phase change: A change in a material, as from solid to liquid or liquid to gas, that occurs abruptly at certain values of temperature and pressure.

Phase diagram: A diagram showing how the phases of a substance relate to its temperature and pressure.

Photolithography: A process using light to lay down patterns for forming integrated circuits.

Photovoltaic cell: A semiconductor device that converts light directly into electrical energy.

Piezoelectric device: A device using a material that generates electricity when squeezed or distorted; conversely, the device changes size or shape when a voltage is applied to it.

Pixel: An individual element of a digital image.

Plasma: An ionized gas, sometimes called the "fourth state of matter."

PN junction: A junction of P- and N-type semiconductors, with the property that electric current can flow in only one direction.

Polar orbit: An orbit that passes over Earth's poles. As Earth rotates, a satellite in polar orbit passes over every point on the planet.

Polarization: The direction of an electromagnetic wave's electric field.

Population inversion: A situation in which more higher level atomic states are populated than are lower level states. Needed for laser action.

Positive charge: The type of electric charge on the proton.

Positron emission tomography (PET): A medical imaging technique using gamma rays from the annihilation of positrons (anti-electrons) released in the decay of radioactive substances.

Potential energy: Stored energy associated with a configuration of objects.

Power: The rate of producing or expending energy. In electrical devices, power is the product of voltage and current.

Precession: The gradual change in direction of a rotating object's rotation axis as a result of an applied torque.

Proton: A positively charged component of the atomic nucleus.

P-type semiconductor: A semiconductor doped so that the dominant free charges are positive holes.

Pulsar: A rapidly spinning neutron star.

Quantum computing: Computing based on the states of quantum-mechanical systems.

Quantum physics: The theory, developed in the early 20th century, that describes physical reality at the atomic scale and below. In this realm, the discrete, "quantized" nature of both matter and energy become important.

Radiation: Heat transfer by electromagnetic waves.

RAM: See **random-access memory**.

Random-access memory (RAM): Memory whose individual storage locations can all be accessed in equal time, as opposed to sequential memory, such as that on magnetic tape.

Read-only memory (ROM): Memory whose state cannot be changed.

Rechargeable battery: A battery in which the passage of electric current from an outside source results in the storage of chemical energy.

Reflection: The phenomenon whereby a wave strikes a material and rebounds at the same angle with which it struck the material.

Refraction: The phenomenon of waves changing direction of propagation when going from one medium to another.

Resistance: The property of a material that describes how it impedes the flow of electric current.

Resistor: A device formulated to have a specific electrical resistance.

Reverse bias: The condition in which a voltage is applied across a PN junction, with positive to the N-type side. Results in very little electric current.

ROM: See **read-only memory**.

Rotational inertia: A measure of an object's resistance to change in rotational motion.

Second law of thermodynamics: A general principle stating that systems tend to evolve from more ordered to less ordered states.

Semiconductor: A material that lies between insulators and conductors in its capacity to carry electric current. The electrical properties of semiconductors are readily manipulated to make the myriad devices at the heart of modern electronics.

Semiconductor memory: Memory made with transistors and other devices. The fastest memory used in computers.

Serial communications: Data transfer that moves one bit at a time, using a single wire.

Shock wave: A very strong, abrupt wave produced when a wave source moves through a medium at a speed faster than the waves in that medium. An example is a sonic boom from a supersonic airplane.

Sliding friction: The frictional force between two surfaces in relative motion; smaller than static friction.

Special relativity: Einstein's 1905 theory that shows how all uniformly moving frames of reference are equivalent as far as the laws of physics are concerned. Requires modification of our commonsense notions of time and space.

Specular reflection: Reflection off a smooth surface that appears shiny and produces an image, as in a mirror.

Spontaneous emission: The emission of light or other electromagnetic energy as an electron jumps spontaneously from a higher energy level to a lower one.

Standing waves: Waves that "stand" without propagating on a medium of fixed size. The vibrations of a violin string are standing waves.

Static electricity: Electricity associated with stationary distributions of electric charge.

Static friction: The frictional force between two surfaces at rest relative to each other.

Static memory (SRAM): Semiconductor memory in which information is stored in the states of flip-flops.

Steady-state theory: The idea, now widely discredited, that the overall structure of the Universe never changes.

Stimulated emission: The emission of light or other electromagnetic energy as an electron jumps from a higher energy level to a lower one, stimulated to do so by the nearby passage of similar electromagnetic energy.

Sublime: To change directly from solid to vapor, without going through the liquid state.

Superconductor: A material that, at sufficiently low temperature, exhibits zero resistance to the flow of electric current.

Superheated: A liquid above its boiling point but nevertheless not boiling.

Supernova: The violent explosion marking the endpoint of massive stars.

Temperature: A measure of the average thermal energy.

Terminal speed: The maximum speed reached by a falling object, which occurs when air resistance becomes equal in magnitude to the force of gravity.

Theory of Everything: An as-yet-undeveloped theory that would describe all of physical reality.

Thermal energy: See **internal energy**.

Thermal energy balance: A state wherein energy leaving a system is balanced by incoming energy.

Thermal pollution: Waste heat dumped to the environment, usually associated with the thermodynamic inefficiency of power plants.

Thermistor: A temperature-measuring device utilizing the property that the resistance of an intrinsic semiconductor decreases with increasing temperature.

Thermocouple: A device that uses the thermoelectric effect to measure temperature.

Thermodynamics: The branch of physics dealing with heat and related phenomena.

Thermoelectric effect: The production of a voltage at a junction of two dissimilar materials when heated.

Toner: The small particles that take the place of ink in dry copying and laser printing (xerography).

Torque: The rotational analog of force; torque depends on force and where that force is applied.

Total internal reflection: Complete reflection that occurs as light attempts to go from a more dense to a less dense medium, as from water to air.

Transformer: A device that uses electromagnetic induction to transform high-voltage/low-current electricity to low-voltage/high-current and vice versa.

Transistor: A semiconductor device with three separate electrical connections, in which current or voltage in one circuit controls current or voltage in another circuit. The basic control element in both digital and analog electronics.

Truth table: A table that displays all possible states of a logic gate.

Volatile memory: Memory that stores information only as long as power is applied.

Voltage: A measure of the energy per unit of electric charge.

Watt: A unit of power, equal to 1 joule of energy per second.

Wave: A traveling disturbance that carries energy but not matter.

Wavelength: The distance between two successive wave crests.

Weight: The force that gravity exerts on an object.

Word: A sequence of binary bits, usually 32 or 64 bits, on which a computer performs operations.

Working fluid: A substance used in refrigerators and engines to transfer heat; often undergoes phase changes in the process.

XOR: See **exclusive OR**.

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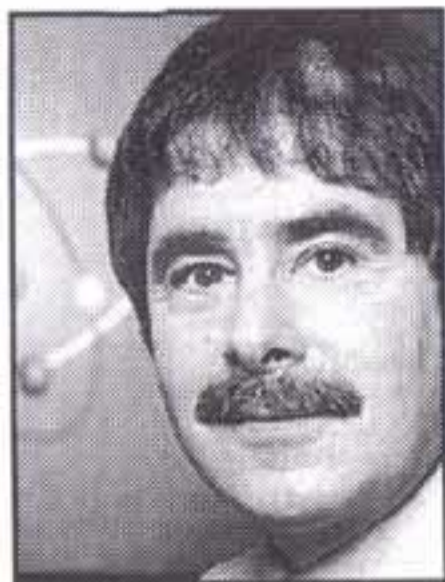
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www.sciam.com/askexpert_directory.cfm. *Scientific American's* "Ask the Experts" page lets you pose questions to scientific and engineering experts, or you can read answers to others' questions.



Professor Richard Wolfson is the Benjamin F. Wissler Professor of Physics at Middlebury College, where he has taught for over 25 years. He holds a Master's degree in environmental studies from the University of Michigan and a Ph.D. in physics from Dartmouth College. Professor Wolfson's research is published widely in scientific journals. He is also a contributor to *Scientific American*. His books include *Simply Einstein: Relativity Demystified*.

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THE GREAT COURSESSM

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Physics in Your Life

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Part 2

Course Guidebook

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Richard Wolfson is Benjamin F. Wissler Professor of Physics at Middlebury College, where he has also held the George Adams Ellis Chair in the Liberal Arts. He did undergraduate work at MIT and Swarthmore College, graduating from Swarthmore with a double major in physics and philosophy. He holds a master's degree in environmental studies from the University of Michigan and a Ph.D. in physics from Dartmouth. Professor Wolfson's published work encompasses such diverse fields as medical physics, plasma physics, solar energy engineering, electronic circuit design, observational astronomy, theoretical astrophysics, nuclear issues, and climate change. His current research involves the sometimes violently eruptive behavior of the Sun's outer atmosphere, or corona. He also continues an interest in environmental science, especially global climate change.

Dr. Wolfson is particularly concerned with making science relevant to nonscientists and to students from all walks of academic life. His textbook, *Physics for Scientists and Engineers* (Addison Wesley, 1999), is now in its third edition and has been translated into several languages. His books *Nuclear Choices: A Citizen's Guide to Nuclear Technology* (MIT Press, 1993) and *Simply Einstein: Relativity Demystified* (W.W. Norton, 2003) exemplify Wolfson's interest in making science accessible to nonscientists. He has also published in *Scientific American* and has produced videotaped courses for The Teaching Company, including *Einstein's Relativity and the Quantum Revolution: Modern Physics for Nonscientists*, *Energy and Climate: Science for Citizens in the Age of Global Warming*, and *Physics in Your Life*. Professor Wolfson has spent sabbaticals at the National Center for Atmospheric Research in Boulder, Colorado; at St. Andrews University in Scotland; and at Stanford University.

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Physics in Your Life

Scope:

Physics is the science that governs the workings of physical reality at its most fundamental level. Thus, physics is important in understanding the ultimate nature of the Universe. But it is equally important in our everyday lives. The commonest actions—such as walking, breathing, or driving a car—are all based on principles of physics. The natural world delights us with a host of physics-based phenomena, from rainbows and snowflakes to the blue of the sky, the daily rotation of our planet, and the celestial companionship of the orbiting Moon. And physics-based technology is ubiquitous in modern life—from the CDs and DVDs that entertain and inform us to the antilock brakes that make driving safer, the global positioning system that helps us navigate about our planet, medical imaging that enhances our health, microwaves that cook our food, airplanes that transport us swiftly about the globe, lasers that scan our supermarket purchases, and the semiconductor electronics at the heart of our computers, cell phones, digital cameras, personal digital assistants, and audiovisual systems.

This course introduces principles of physics through their application to everyday life. It's more than a course in physics and more than a laundry list of "how things work." Rather, it combines the two, offering a back-and-forth interplay between everyday applications of physics and the physics principles needed to understand them. Applications include the simplest everyday activities, natural phenomena that affect our everyday lives, and especially, modern technology. Physics principles covered range from Newton's laws of motion, known for hundreds of years but still vitally relevant, to concepts from atomic and quantum physics that underlie such diverse technologies as semiconductor electronics, lasers, and medical imaging.

The course is organized into six modules of six lectures each. The first five modules deal with specific realms of physics and related applications; the sixth is a potpourri of physics applications that draw from more than one of the earlier modules. Although there's no obviously straightforward path through the myriad applications included here, the lectures are designed to build on each other and to flow smoothly from one to the other. *Physics in Your Life* is aimed at intelligent nonscientists, and the presentation of physics concepts and applications is entirely nonmathematical.

Given that the course is presented on audiovisual media, the first module—**"Sight and Sound"**—begins with the technology behind CDs and DVDs, not only explaining how these work but raising questions that lead to the basic principles of light and sound. Subsequent lectures explore these principles in application to such diverse topics as rainbows, optical fibers for communications, musical instruments, and laser vision correction.

“**Going Places**” looks at motion and its applications, from simple walking to modern automobile technology, airplane flight, and space travel. This module is based on Newton’s laws, generalized to include such diverse topics as fluid motion, conservation of energy, and the dynamics of space flight from communications satellites to interplanetary exploration.

“**Plug In, Turn On**” explores the electromagnetic basis of so many contemporary technologies and natural phenomena. Matter itself sticks together through electrical interactions, while the intimate relations between electricity and magnetism are at the heart of technologies ranging from electric motors and generators to videotapes and credit cards. We’ve learned numerous ways to produce electrical energy, and we respect not only the good it can do but also the dangers it poses. Finally, electricity and magnetism join to make possible the electromagnetic waves that include visible light and that enable the growing host of wireless technologies in our everyday lives.

“**From Atom to Computer**” starts with basic ideas in atomic physics and builds through explanation of the semiconductor materials at the basis of today’s electronics; the operation of the transistors that are the essential electronic components; the agglomeration of close to a billion transistors in today’s most sophisticated integrated circuits; the simple logical operations that underlie all our computers can do; and the structural organization of an entire computer.

The fifth module, “**Fire and Ice,**” introduces concepts and applications related to heat. Lectures range from “Physics in the Kitchen” to “Life in the Greenhouse,” the latter a look at how principles of thermal physics establish Earth’s climate and how we humans may be changing that climate. “The Tip of the Iceberg” describes the thermal response of materials, including the unusual behavior of water in both liquid and solid form—a behavior with enormous implications for life on Earth. The module ends with a look at humanity’s appetite for energy in the face of limitations posed by the laws of thermodynamics. Those laws themselves are the subject of “Like a Work of Shakespeare,” a lecture so titled because one such law has been deemed as essential to an educated person as the Bard’s writings.

The sixth module is a potpourri of applications and principles from the specific to the cosmic. “Your Place on Earth” describes the workings and increasingly pervasive applications of the space-based Global Positioning System (GPS). “Dance and Spin” looks at applications of rotational motion from dance to pulsars. “The Light Fantastic” explores the operation of lasers and their applications in everything from supermarket scanners to the Internet. “Nuclear Matters” looks at the behind-the-scenes roles that nuclear physics plays in our lives. “Physics in Your Body” emphasizes modern medical techniques, such as MRI and particle-beam treatments for cancer. The course ends with “Your Place in the Universe,” tracing the history of your own body from the earliest events of the Big Bang.

Module Three: Plug In, Turn On

Lecture Thirteen

The Electrical Heart of Matter

Scope: Electricity plays a huge role in our technological society. Electrical energy is our most convenient, most easily transported form of energy. Working with its close cousin, magnetism, electricity powers motion from disc drives and dentists’ drills to fans and air conditioners, subways and high-speed trains. Electromagnetism lets us store information on credit cards, video- and audiotapes, and computer discs. The electronic gadgets so pervasive in our lives all involve the unusual and malleable electrical properties of the element silicon. In the natural world, electricity powers dramatic thunderstorms while magnetism protects us from harmful solar radiation. Electricity determines the very structure of matter on the scale of atoms to molecules, and electrical impulses govern our heartbeats and mediate our bodies’ internal communications.

Outline

- I. How many electrical devices have you used today?
 - A. Many! It’s almost impossible to get through a day of life in today’s technological society without using literally dozens of electrical and electromagnetic devices.
 - B. You yourself are electrical, too. From your heart to your nervous system, electrical signals regulate your body. Physicians use electricity and magnetism to probe your body in noninvasive ways and even to heal broken bones. (More on this in Lecture Thirty-Five.)
 - C. Even the individual atoms that make up your body and everything else are held together electrically. Electrical forces join atoms into molecules and, ultimately, facilitate the cellular processes, including DNA replication, that keep us alive and growing.
- II. Electricity—specifically, *electric charge*—is a fundamental property of matter. The two kinds of charge, *positive* and *negative*, were named by Ben Franklin. The names do not connote a presence or absence but just a difference between these two complementary properties.
 - A. The tiny but relatively massive protons found in the nuclear cores of atoms carry positive charge. Electrons, with only about 1/2000 the mass of the protons, carry negative charge. The negative charge on every electron has exactly the same magnitude as the positive charge on every proton.

B. Opposite electric charges attract, and like charges repel, in both cases with a force that weakens with increasing distance between the charges. A more sophisticated way of looking at this interaction is to say that an electric charge creates an *electric field*—a kind of invisible influence—in the space around it and that other charges experience forces when they encounter this field. A more familiar field is the gravitational field.

- 1.** The mutual repulsion of like charges is the reason a car's metal body protects you from lightning.
- 2.** A lightning strike to the car delivers a significant amount of charge that, if it passed through your body, could be fatal. But mutual repulsion causes the charge to remain on the outside of the car's metal skin, bypassing everything inside the car. That's what protects you—not, as is often believed, the car's rubber tires.

C. In the standard scientific unit system, charge is measured in *coulombs*, named for the French physicist Charles-Augustin de Coulomb (1736–1806). One coulomb is roughly the magnitude of the charge on about 6 million trillion (6×10^{18}) electrons or protons.

III. Matter as we know it owes its structure largely to this electric force between charges.

- A.** Protons join (via a nonelectrical force) with neutral particles, the neutrons, to make positively charged atomic nuclei.
- B.** Positive nuclei attract electrons, which move in a “quantum cloud” about the nucleus. The number of electrons is equal to the number of protons in the nucleus; thus, atoms are electrically neutral. The chemical properties of an atom are determined by the number of electrons, hence by the number of protons—the so-called *atomic number*.
- C.** Although atoms are electrically neutral, they can still bond together electrically to make molecules, in some cases, by “sharing” electrons and, in other cases, by donating one or more electrons to another atom, resulting in strong electrical forces between the now-charged atoms, also called *ions*.
- D.** The electric force is very strong; the electric force between two protons is some 40 powers of 10 stronger than the gravitational force between them. That very strength, combined with the fact that there are two kinds of electric charge, results in neutral assemblages of matter and makes us unaware of the fundamentally electrical nature of matter. A huge object such as Earth, for example, is very nearly electrically neutral and, thus, shows only the most subtle electrical effects. But because the much weaker gravitational force does not involve positive and negative “charges,” the massive Earth exhibits substantial gravitational effects.

E. Even electrically neutral molecules often exhibit electrical effects, because electric charge is distributed unevenly over the molecule. Water provides a great example: opposite ends of the water molecule carry opposite electric charge, causing these ends to attach themselves to other charges. That's why water dissolves a substance such as salt, which consists of positive and negative ions. It's also why water-containing substances get heated in a microwave oven. The electric field of the microwaves “grabs” water molecules and flips them back and forth. As the molecules jostle together, they generate heat. Because water exhibits a greater charge separation than most molecules, only water-containing substances tend to get heated. (More on this in Lecture Twenty-Eight.) Very weak electric forces associated with such uneven charge distributions are responsible for some molecular bonding, such as in ice.

IV. Electric charge plays a direct role in a number of practical devices.

- A.** In ink-jet printers such as most of us use at home, tiny ink drops are given electric charge and are accelerated and steered by electric forces so that they land at just the right spot on the paper.
- B.** In copiers and laser printers, electric charge is laid down on a light-sensitive drum. The image to be copied is projected, either optically or with a laser beam, onto the drum. Where light strikes the drum, it becomes a good electrical conductor, and the charge is neutralized. But charge remains in the dark areas. Then, tiny particles of plastic *toner* are transferred to the drum. They stick, via the electric force, only to the charged areas—where the image was dark. The drum then rolls over a sheet of paper, which has been given an even greater charge, and the toner transfers to the paper. Finally, the paper passes through a pair of heated rollers, which melt the toner particles, fusing the image permanently onto the paper.
- C.** Electric charge also helps clean our air. Both home air cleaners and the pollution-control systems of electric power plants use *electrostatic precipitators* to remove harmful particulate matter. Particle-laden air flows through a metal chamber containing thin wires that carry a strong negative charge. Charge is crowded on the thin wire, making for a strong electrical repulsion. As a result, some negative charge is transferred from the wires to the passing particles. The particles are then attracted to the positively charged chamber walls, where they stick. The walls are mechanically tapped at periodic intervals, causing the particles to fall into a hopper for disposal. Such devices can remove up to 99.9 percent of the particulate matter in the exhaust from a typical coal-burning power plant.

Suggested Reading:

Going Deeper:

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 11, sections 1–2.

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 22 and pp. 649–650.

Questions to Consider:

1. The electrical force between an electron and a proton is far stronger than the gravitational force between them. Yet large objects such as Earth exhibit strong gravity but very little electrical force. Why?
2. Even though a water molecule is uncharged, it still exhibits significant electrical properties. Why?

Lecture Fourteen

Harnessing the Electrical Genie

Scope: Most of our electrical technology is based not on stationary electric charges—so-called *static electricity*—but on *moving* charge. Any flow of electric charge constitutes an *electric current*. We build electric circuits, providing complete paths for the flow of current, and with these circuits, we make moving electric charge perform a host of useful tasks. Two important electrical quantities characterize charge flow in circuits: *Current* itself is a measure of the rate of charge flow, and *voltage* measures the energy imparted to the charges. Charge flows more easily in some materials than in others, and we exploit these differences in such devices as lightbulbs and electric heaters. More sophisticated control of charge flow leads to the myriad electronic devices that have become ubiquitous in our society.

Electricity is immensely useful, but it's also hazardous. Charge flow through our bodies is dangerous because it can disrupt the minute electrical impulses associated with the nervous system, control of muscles, and especially, the pacing of the heartbeat. Modern electrical systems take several approaches to protecting us from the dangers of the “electrical genie.” When our bodies’ internal electrical systems go awry, electrical devices save lives by restoring normal electrical rhythms.

Outline

- I. A net flow of electric charge constitutes an *electric current*. A current of one *ampere* (named for the French physicist André-Marie Ampère, 1775–1836) corresponds to a flow of one coulomb per second, or about 6 million trillion (6×10^{18}) electron charges every second. Typical currents in household wiring range from under 1 ampere to 15 or 20 amperes.
 - A. Electric current flows easily in materials that contain free electric charge; such materials are *conductors*.
 1. The most common conductors are metals, in which the outermost electrons leave their individual atoms and roam freely throughout the metal, constituting a “sea” of free electrons that can respond *en masse* to electric forces and, thus, carry electric current.
 2. Solutions, such as salt water, are also conductors. Dissolved substances, including salt, exist as negative and positive ions that can move freely to carry current. Our blood and body tissues are examples of ionic conductors. Minute currents associated with the movement of ions through cell membranes are what carry nutrients into and waste materials out of our living cells.

3. *Plasmas*, or ionized gases, are excellent conductors. Plasmas are rare on Earth because they generally require very high temperatures; they're found in lightning bolts, flames, fluorescent lamps, and so-called plasma TV displays. But plasmas are important on the cosmic scale; the stars are plasma, and plasma probably constitutes 99 percent of the visible Universe. Because plasmas conduct electric current, they behave very differently from ordinary gases.
 4. *Semiconductors* fall between insulators and conductors. Their precisely controllable electrical properties are the enabling basis of modern electronic devices (more on this topic in Module Four).
 5. *Superconductors* are materials that, at very low temperatures, conduct electric current perfectly, with no loss of energy. A room-temperature superconductor remains an elusive "holy grail" for physicists and materials scientists.
- B.** In contrast, materials in which electrons are bound to individual atoms are *insulators*, which cannot easily carry current.
- C.** It's no coincidence that the best conductors—metals—are opaque and shiny, while many insulators, such as glass and plastics, are often transparent. That's because light is an electromagnetic wave. Impinging on a metal, the light sets the free electrons vibrating, and they re-emit electromagnetic waves right back. That's the process of reflection. The bound electrons in an insulator have much less interaction with the light wave and serve only to slow it slightly. That's what gives rise to the phenomenon of refraction.
- II.** Except in superconductors, electric charge flowing in a conductor undergoes collisions with the atoms of the material and gives up energy through heating of the conductor. Therefore, energy is required to force current through a conductor. The property of a conductor that describes its imperfect conduction is its electrical *resistance*. The bigger the resistance, the more energy it takes to force charge through the conductor. That, in essence, is an English statement of the famous *Ohm's law*.
- A.** *Voltage* is a measure of the amount of energy imparted to charges as they move between two points. Specifically, voltage is the energy (measured in joules) per coulomb of charge. For example, a 1.5-volt flashlight battery imparts 1.5 joules of energy to each coulomb of charge that flows from the battery through the flashlight bulb and back to the opposite terminal of the battery. A 9-volt battery imparts 9 joules to each coulomb of charge, and the 120-volt electric power available at standard wall outlets imparts 120 joules. But a higher voltage battery doesn't necessarily mean more power, because the chemical reactions that separate positive and negative charge in a smaller battery simply can't produce much electric current. (The volt is named after the Italian

physicist Alessandro Giuseppe Antonio Anastasio Volta, 1745–1827, who invented the electric battery.)

- B.** Because *power* is energy per time, multiplying voltage (energy per charge) by current (charge per time) gives electric power (measured in joules per second, or *watts*). A standard 100-watt lightbulb running off 120-volt household power, for example, has a current of about 0.83 amperes ($0.83 \text{ amperes} \times 120 \text{ volts} = 100 \text{ watts}$). But you can also buy a 100-watt bulb for your camper, which has a 12-volt electrical system. With 1/10 the voltage (energy per charge), it must move 10 times as much charge (10 times the current) to get the same power.
1. This lightbulb example shows that you can achieve a given power with either a high voltage and low current or a low voltage and high current. But high currents result in a lot of collisions in the current-carrying conductors and, thus, in significant energy loss.
 2. Long-distance power transmission lines operate at very high voltages—hundreds of thousands of volts—precisely for this reason: They avoid loss of energy to heating of the wires. On the other hand, such voltages would be dangerous in household wiring, so the voltage is reduced and current is increased close to individual buildings (more on this in Lecture Seventeen). This is also the reason why, decades ago, car batteries were changed from 6 volts to 12 volts.
- III.** Electric current can be hazardous to the human body. You feel a tingling sensation at currents as small as a few thousandths of an ampere, and at a hundredth of an ampere or so, your muscles contract involuntarily and you may not be able to let go of whatever electrical conductor you've contacted. Even 1/10 to 2/10 of an ampere is enough to disrupt your heartbeat, throwing the heart into often-fatal fibrillation. At higher currents, breathing stops, but the victim actually has a higher chance of survival. All these currents assume dry, unbroken skin; much smaller currents within the body itself may be harmful.
- A.** Why don't we put up "Danger: High Current" signs rather than "Danger: High Voltage" signs? Because the human body (at least with dry, unbroken skin) is a relatively poor conductor; a high voltage is required to push significant current through it.
- B.** Measures of voltage always involve two points, such as the two terminals of a battery. To say a power line is at high voltage means that charges flowing between it and, say, the ground would gain large amounts of energy. Touch the power line and the ground, and you're in trouble. But a bird landing on the line is unharmed, because it isn't contacting two points with a voltage between them.
- C.** With electrical devices and appliances, there's a danger that defective wiring could connect exposed metal parts to dangerous voltage. If you

contact that metal while also in contact with the ground, a dangerous current might flow through you. That's the reason many electrical devices have a special three-wire grounding plug. Then, if there's a fault in the device, current flows harmlessly to ground and blows a fuse or circuit breaker. A more sophisticated protection device is the *ground-fault circuit interrupter (GFCI)*, which senses a slight imbalance in current flowing out one wire and back the other and shuts off the current on the assumption that the extra current might be flowing through your body. GFCIs are required on outlets in kitchens and bathrooms and around swimming pools and other damp locations.

- D. The very disruption of the body's internal electrical system that makes electricity dangerous is also the basis of lifesaving devices, including defibrillators and pacemakers.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 23.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 12, section 1.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapters 27–28.

Questions to Consider:

1. Why can a bird land on a high-voltage power line without being harmed?
2. Water and electricity are not a safe mix. Why not? What does this suggest about the electrical resistance of the human body under different conditions?

Lecture Fifteen

A Magnetic Personality

Scope: Electricity is intimately related to magnetism. Ultimately, magnetism in our world arises from *moving* electric charges, and the force of magnetism acts, fundamentally, on *moving* charges. We exploit this relation in a vast range of electromagnetic devices, from the obvious—such as motors and loudspeakers—to less intrusive but essential devices, including the circuit breakers that protect our homes from electrical fires or the electromagnetic system that moves the lens in a CD or DVD player to keep the laser beam precisely focused on the spinning disc. On a grander scale, our planet is itself a magnet—a fact that is important in such diverse phenomena as compasses and northern lights. More significantly, Earth's magnetism protects us from dangerous cosmic radiation.

Outline

- I. Although magnetism is most familiar to us in the form of everyday magnets, such as those we use to stick notes to refrigerators, magnetism is, in fact, a fundamental property of nature that is intimately associated with electricity. As with electricity and gravity, it's convenient to describe magnetic interactions in terms of a *magnetic field*. You can think of the field as tracing out the directions in which a compass needle would align itself.
 - A. The source of all magnetism in our world is *moving electric charge*.
 1. In magnets, those moving charges are the electrons that orbit and spin within atoms, making them miniature magnets. In a handful of materials, especially iron, interactions among atoms can result in the individual atomic magnets aligning to give the large-scale magnetism we observe in these materials. In unmagnetized iron, the individual atomic magnets point in random directions, so there's no bulk magnetism. But bring a magnet nearby and the effect is to align the atoms in the unmagnetized material, causing it to be attracted to the magnet. That's why a magnet attracts iron. Our association of everyday magnetism with iron and related materials obscures the more fundamental and universal nature of magnetism.
 2. Electric currents, including those flowing in our technological devices, are examples of moving electric charge; thus, they, too, create magnetism. An *electromagnet* is simply a coil of current-carrying wire. As long as the current flows, the coil acts just like a magnet. The magnetism can be strengthened by winding the coil around a magnetic material like iron, but this is not essential. Electromagnets can impose magnetism on suitable magnetic materials; that's what happens in an audio- or videotape recorder,

where time-varying current is supplied to a small coil of wire as tape moves past. The pattern of the current, itself reflecting the information to be recorded, is stored permanently in the orientation of magnetic regions on the tape. Electromagnets made with conventional conductors, like the simple demonstration done in the video, need a battery or other source of power to keep the current flowing. But electromagnets made with superconductors carry current indefinitely with no need for power—as long as they're kept cold. The magnets used in MRI—magnetic resonance imaging—are examples.

3. The magnetism of stars and planets arises in the same way. Earth, for example, has an outer core of liquid iron. A complex interaction between Earth's rotation and heat-driven circulation results in electric currents in this core; these produce Earth's magnetism. For reasons we still don't fully understand, Earth's magnetic field reverses direction roughly every million years. The directions of the field become imprinted in the rocks that form as the ocean floors open, and geophysicists use these rocks as a giant tape recorder. The Sun's magnetism also arises from electric currents flowing in the gaseous star, but it is much more complex and reverses roughly every 11 years. Sunspots are visual manifestations of regions of intense solar magnetic field, which are often the source of violent eruptions of matter from the Sun. These can have a direct impact on Earth.

B. Magnetism not only arises from *moving* electric charge, but the fundamental effect of magnetism is to exert forces on moving electric charge. Using the field concept, we say that a moving electric charge creates a magnetic field and that other moving electric charges respond to that field. The magnetic force generally causes charged particles to move in circular or spiral paths. Examples of the magnetic force in action abound in both nature and technology:

1. The attractive or repulsive force between magnets ultimately results because the magnetic field created by the moving charges in the atoms of one magnet exerts a force on the moving charges in the atoms of the other magnet.
2. In a tube TV or computer monitor, the electrons that "paint" the picture on the screen are "steered" to the right spot on the screen by the magnetic field of an electromagnet wound around the glass neck of the picture tube.
3. The *magnetron* that produces microwaves in a microwave oven is a special vacuum tube in which electrons whirl around in circular paths under the influence of a magnetic field. The frequency of their circular motion—about 2.4 billion times per second—is determined entirely by the magnetic field. The whirling electrons emit microwaves of the same frequency, which are guided into the

oven to cook your food (more on this in Lectures Eighteen and Twenty-Eight). On a much larger scale, magnetic fields guide charged particles around circular paths in the huge particle accelerators physicists use to study the fundamental structure of matter.

4. Earth's magnetic field exerts forces on high-energy charged particles from the Sun—particles that would be harmful to living things if they reached Earth's surface. Earth's field deflects the particles, channeling them on paths that converge near the poles and, when the particles slam into the upper atmosphere, create auroras.

C. It's no different with electric currents. Composed of moving charges, current-carrying wires also respond to the magnetic force. This force is the basis of a great many technological devices.

1. In electric motors, current flows through coils mounted on a rotating structure. The coils experience a force from stationary magnets, and a clever arrangement reverses the coil current so as to keep the motor rotating in the same direction. Electric motors power everything from electric toothbrushes to gas-electric hybrid cars to railroad locomotives.
2. In loudspeakers, current from an audio amplifier flows through a cylindrical coil suspended over a cylindrical magnet. Current flowing through the coil varies with the sound being reproduced, causing a varying force that moves the coil back and forth. The coil is attached to a flexible cone, which creates sound waves as it moves.
3. The focusing mechanism of a CD or DVD player works like a loudspeaker, except that a lens is mounted on the coil. A light sensor detects an out-of-focus condition and sends a signal that is amplified to pass current through the coil in the right direction so that the lens moves to achieve sharp focus.
4. Current flowing to your household wiring passes first through a small electromagnet in the circuit breakers mounted in a central breaker panel. If the current becomes so large that wires would become dangerously hot—15 or 20 amperes in typical household wiring—the electromagnet pulls on a piece of magnetic material connected to an electric switch. This shuts off the current until the breaker is reset.

II. Magnetic technologies will play an increasingly important role in the future. Two examples include:

- A.** Maglev vehicles, which "fly" just inches above an electrically conducting track, supported by the magnetic force.

- B.** Nuclear fusion reactors, in which a gas of charged particles at very high temperature (about 100 million degrees) is confined by magnetic fields and undergoes nuclear fusion, producing copious amounts of energy. If we were to perfect this process, the water in Earth's oceans could satisfy humankind's energy needs for 300 billion years!

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 24.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 12, section 4.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 14, sections 1–3.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapters 29–30.

Questions to Consider:

1. How is electricity fundamental to the behavior of an ordinary refrigerator magnet?
2. What would happen to an electric motor if it didn't incorporate a mechanism for reversing the direction of the current in the moving coils?

Lecture Sixteen

Making Electricity

Scope: To make electric current and keep it flowing, we need devices that can separate positive and negative charge and keep them separate, forcing them to flow through any external circuit we might connect. Such devices include the familiar chemical batteries and a host of more obscure devices, including photovoltaic cells, fuel cells, piezoelectric devices, and thermoelectric devices. But our predominant means of producing electric current is through *electromagnetic induction*, yet another phenomenon involving an intimate connection between electricity and magnetism. Electromagnetic induction is the basis for electric generators and a host of other devices.

Outline

- I. We make the energy associated with electric currents by converting other forms of energy into what is ultimately energy involving the separation of electric charge. Here, we look at several devices, some familiar, others less so, that achieve this conversion.
 - A. *Batteries* are familiar devices in which chemical reactions drive the charge separation. A battery maintains a fixed voltage between its positive and negative terminals. If an external circuit is connected, this voltage difference drives current through the circuit, supplying it with energy that comes ultimately from the chemicals in the battery (which itself is a form of electrical energy associated with the charge distribution on the individual molecules). In some kinds of batteries, the chemical reactions are reversible; these batteries are *rechargeable*. Sending current from an external source through the battery from positive to negative stores energy in the battery, thus recharging it.
 - B. *Photovoltaic (PV) cells* use semiconductors (more in the next module) to capture the energy in light and use it to separate positive and negative charge. Now used primarily in spacecraft and remote locations, PV cells have great potential for converting sunlight to electrical energy on a larger scale.
 - C. *Fuel cells* are chemical devices, somewhat like batteries, except that they are continuously fed with the chemicals that react to produce electrical energy (hence, *fuel cell*). One type of fuel cell uses hydrogen and oxygen, which react on a catalytic surface (a material that participates in a chemical reaction but is not consumed) to produce electrical energy and the cell's only byproduct, water. Fuel cells can be highly efficient and hold great promise, both as mobile energy sources for transportation and as stationary sources supplying individual homes

and larger buildings. Fuel cells have long been used on spacecraft and in other specialized applications and are now beginning to find more everyday applications. But energy must be used to create the cell's hydrogen fuel; alternatively, the cell can use products derived from fossil fuels.

D. *Piezoelectric* devices use certain crystals that produce separated charge when compressed. These are not useful for producing electric power but are good for short bursts of high voltage. Such devices are used widely in igniters for gas stoves and grills. Old-fashioned, low-cost phonograph pickups and microphones used piezoelectric devices. In a converse use, applying a voltage to a piezoelectric device causes it to deform; this property is used in micro-positioning devices, ultrasonic sound sources, and a host of other applications.

E. The *thermoelectric effect* occurs in a circuit including two junctions between different materials. If the junctions are at different temperatures, a voltage develops that drives a current; the effect is to convert thermal energy into electrical energy. Although not very efficient, this effect is used in thermoelectric generators that power spacecraft to the outer solar system, where solar energy would be insufficient. Heat generated by decaying radioactive materials provides the energy. The effect is also used in temperature-measuring devices called *thermocouples*. Because the thermoelectric effect is reversible, it can be used for cooling as well. Medical samples are often preserved with thermoelectric coolers, which are quiet and have no moving parts.

II. None of the processes just described provides any significant portion of the world's electrical energy, even though they may be important in specialized applications. The vast majority of our electrical energy comes, instead, from *electric generators*, whose operation depends on yet another connection between electricity and magnetism. Here, we explore this connection in the abstract; in the next lecture, we'll look at generators and many other related applications.

A. In the 1830s, the English scientist Michael Faraday and the American Joseph Henry discovered that magnetism can be a source of electricity. In particular, they found that *changing* magnetism produces electrical effects. This can occur in any of a variety of ways.

1. Move a magnet near a closed electric circuit that contains no battery or other source of energy, and a current nevertheless flows. The current does not flow if the magnet is stationary relative to the circuit.
2. Moving the circuit while holding the magnet stationary produces exactly the same effect. Evidently, only *relative* motion matters. (Aside: This fact made a big impression on Einstein, who mentions "the reciprocal electrodynamic action of a magnet and a conductor"

in the second sentence of his famous 1905 paper introducing the theory of relativity.)

3. It doesn't matter whether the magnet is a permanent magnet or an electromagnet (no surprise here; both involve *moving* electric charge).
4. With both coils stationary, *changing* the current in one coil—thus changing its strength as an electromagnet—produces a current in the second coil.

B. What all these experiments have in common is *changing* magnetism. What Faraday and Henry discovered, in slightly more sophisticated language, is that *a changing magnetic field creates an electric field*. It doesn't matter whether the magnetic field changes because a magnet moves near a coil, or a coil moves near a magnet, or because a magnetic field changes in time without any movement. In all cases, changing magnetism becomes a source of electricity. This process is called *electromagnetic induction*, and the electric field created is an *induced electric field*.

1. If an electric circuit is in the vicinity of the changing magnetic field, then the induced electric field drives a current in the circuit. In this way, energy has been transferred to the circuit from whatever agent was causing the change in magnetic field.
2. Induction is a fundamental process, responsible for a host of natural, as well as technological, phenomena. The equation that describes induction quantitatively is one of the four fundamental equations of electromagnetism and is known as *Faraday's law*.
3. There's no free lunch, and the agent changing the magnetic field really does have to work to make this happen. Otherwise, we'd get electrical energy for nothing—and we wouldn't have to burn all that coal or fission all that uranium to make our electricity. This is the electrical manifestation of the important *conservation-of-energy* principle. Incidentally, the requirement that energy be conserved determines the direction of the induced current.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 25.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 14, section 4.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 12, section 4.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 31.

Questions to Consider:

1. A battery eventually wears out. Why? A fuel cell doesn't wear out. Why not?
2. If you connected a lightbulb with wires to the two poles of a magnet, would it light? If not, how could you, at least in principle, use the magnet to light the bulb?

Lecture Seventeen

Credit Card to Power Plant

Scope: Electromagnetic induction is the basis for electric generators and a host of other everyday devices. Moving a conducting material near a magnet, or vice versa, generates electric current in the conductor. Huge power generators work this way, as do the devices that “read” your credit card when you swipe it at a store’s checkout counter or gas pump, your audio- and videocassette players, your car or bicycle speedometer, microphones and some computer disc drives, and some stovetops. We also use induction to mediate between different electric circuits, enabling systems as vast as the power grid and as small as an electric toothbrush. The uses for electromagnetic induction in our technological society are virtually endless.

Outline

- I. Electromagnetic induction is, ultimately, a process producing electrical energy at the expense of whatever is causing a changing magnetic field. When that changing field results from physical motion, then induction converts mechanical to electrical energy.
 - A. *Electric generators* play a vital role in modern society, producing virtually all of our electrical energy, which is about one-third of our total energy. A typical generator consists of a coil of wire wound on a rotating shaft, surrounded by either permanent magnets or electromagnets. (In large power plants, they’re always electromagnets—which is one reason that it’s hard to get power restored after a major blackout.) As the coil spins, it experiences a changing magnetic field, and an electric current flows in the coil. Rotating electrical contacts pass the current to stationary “brushes,” from which the current flows to power external circuitry. A generator is essentially a motor in reverse; in comes mechanical energy, and out goes electrical energy.
 - B. The conservation-of-energy principle is very much at work in generators. If there’s nothing connected to the generator, then it’s very easy to turn. But if the generator is supplying electrical energy, then the agent turning the generator must supply mechanical energy at the same rate. Think about this next time you leave a light burning! Something is having to work that much harder to turn a generator, and that much more coal is being burned, or uranium is fissioning, or mountain ridges are being populated with wind turbines! You can see the same effect if you turn on your car’s headlights while it’s idling slowly; the extra load on the electric generator (“alternator”) that charges your car’s battery

causes the engine to work harder and, thus, slow or even stall. Incidentally, it would take about 100 people, cranking away all the time at generators, to produce all the energy used by a typical U.S. resident (more on this in Lecture Thirty).

C. Motors and generators are opposites. The former take in electrical energy and produce mechanical energy; the latter take in mechanical energy and produce electrical energy. The same device can be used for either purpose—a property that's put to good use in hybrid cars, with their regenerative braking, and in so-called pumped-storage power plants.

II. Another use for induction is to “read” information stored in magnetic materials. Information is encoded as regions of varying magnetism (the encoding is done with an electromagnet carrying varying electric current). The magnetic material is then moved past a “head,” consisting of a coil of wire, typically wound around an iron core with a small gap. The changing magnetic field associated with the moving magnetic material induces current in the coil, and this current carries the information encoded in the magnetic material.

A. In analog audiotape recording, a continuously varying pattern of magnetization corresponds to the music or other sound recorded on the tape. In digital recording, the magnetization is one direction or the other, corresponding to a digital 1 or 0. The speed of the tape and density with which differing strengths of magnetization can be packed onto the tape determine the maximum frequency that can be recorded.

B. Video images contain much more information than audible sounds. Although videotape recording works on the same basic principle as audiotape, the technology must be more complicated to deal with the greatly increased information. In a videocassette recorder (VCR), the video heads actually spin as the tape moves past them. This results in a much higher effective speed. The tape crosses the spinning head at an angle, which means that the information is written in strips that extend diagonally across the width of the tape.

C. Older computer disc drives also used induction to “read” information stored on the disc. In a hard drive, the disc spins rapidly under a tiny head that literally flies—supported by aerodynamic forces—well under a millionth of a meter from the spinning disc. Induced currents in the head coil would carry the information that was on the disc. (Modern computer hard discs use a different principle, in which the changing magnetic field of the spinning disc causes a change in the electrical resistance of the head.)

D. Magnetic strips on credit cards and in similar applications store information that is read by passing the strip past a head very much like that in an audiotape player.

E. Some microphones, most phonograph pickups, and electric guitar pickups also use induction. In a microphone, a magnetic metal diaphragm vibrating in response to sound waves alters the magnetic field of a permanent magnet, inducing a current in a nearby coil; the current is a faithful analog of the sound waves. In a phonograph pickup, the needle vibrating in the grooves of a record moves a tiny coil, a magnet, or a piece of iron to vary a magnetic field and induce a current in a coil. In an electric guitar, vibrating steel strings alter the field of a permanent magnet, again inducing a current in a nearby coil.

F. Induction is also useful in detecting motion, particularly rotational motion. Modern speedometers, tachometers, and similar instruments often use a tiny magnet mounted on a rotating shaft or wheel. As the magnet passes a stationary coil, it induces a pulse of current. The instrument counts the number of pulses in a given time and displays the result as a rotation rate or speed.

III. Toothbrush time! How's that electric toothbrush work? There's no electrical connection between the brush and its base. Again, it's induction at work.

A. The previous lecture showed that changing magnetic field caused by a changing current in one coil induces an electric current in a nearby coil. This is what happens in the electric toothbrush: The base is plugged into the wall, where the alternating current drives a changing current in a coil built into the base. When the brush is standing on the base, a coil in the brush experiences this changing field, and a current is induced. The current is changed to direct current (more on this later) and used to charge the brush's batteries.

B. This is the principle of the *transformer*, a device that uses changing current in one coil to induce current in another coil. Transformers can convert electricity at high voltage and low current to low voltage and high current and vice versa.

1. Small transformers take the 120-volt power-line voltage down to levels safe to use in electronic equipment.

2. Large transformers step up the voltage from power generators for long-distance power transmission (more efficient at high voltage; recall Lecture Fourteen) and back down for distribution in a city and, ultimately, to individual homes.

3. Your car (unless it's a diesel) runs because a transformer—the ignition coil—steps the voltage from the car's battery up from 12 volts to the roughly 25,000 volts needed to produce the spark that ignites the gasoline/air mixture in the engine's cylinders.

4. Transformers work by induction and, therefore, require *changing* current. Thus, they work fine with alternating current but not with direct current (one of the reasons the power grid uses AC). In DC applications, as in stepping up the output of a photovoltaic cell to

standard 120-volt household levels, or in the ignition coil of a car, DC current must be interrupted to produce the change that leads to induction. (An aside: In older cars, that interruption was accomplished by the distributor points—basically a mechanical switch opened by a rotating shaft. In modern cars, the interruption is done electronically, triggered by an inductive pickup from a magnet on the rotating shaft. That's part of the reason today's cars need tune-ups much less frequently.)

- IV. Although very useful, induction is an occasional nuisance. When conductors move near magnets, the induced currents dissipate energy and act like a kind of electromagnetic “friction.” This effect can be put to good use in electromagnetic brakes, which bring spinning machinery to a rapid stop by energizing a nearby electromagnet.

Suggested Reading:

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 12, sections 2, 3, 5.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 14, section 5.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapters 32–33.

Questions to Consider:

1. Some trains and power saws use electromagnetic braking, in which an electromagnet is energized near a spinning metal disc (typically aluminum, which is not a magnetic material). The disc quickly stops, warming in the process. Why?
2. Why don't transformers work with direct current?

Lecture Eighteen

Making Waves

Scope: Electricity and magnetism are intimately related. Moving electric charge is a source of magnetism, and changing magnetic field is a source of electricity. If there were such a thing as magnetic charge— isolated north and south magnetic poles—we might expect that moving magnetic charge would be a source of electricity. What about changing electric field? Is it a source of magnetism? In the 1860s, the Scottish physicist James Clerk Maxwell (1831–1879) proposed that it should be. He modified Ampère's law, describing how magnetism arises from moving electric charge, to include a term involving changing electric fields as an additional source of magnetism. Maxwell then showed that the ability of each kind of field to produce the other could result in a structure of combined electric and magnetic fields, each field continuously changing and regenerating the other field, that would propagate through space as a wave. Maxwell calculated the speed of these waves and found it to be equal to the known speed of light. Suddenly, the wave nature of light was understood, and the whole science of optics (Module One) became a branch of electromagnetism.

By 1887, the German physicist Heinrich Hertz (1857–1894) had demonstrated the production and reception of electromagnetic waves. By 1896, the Italian physicist and inventor Guglielmo Marconi (1874–1937) had developed a wireless telegraph using electromagnetic waves capable of transmitting information several miles, and in 1901, Marconi achieved the first transatlantic wireless communication.

A vast array of modern technology stems directly from Maxwell's discovery of electromagnetic waves and its application by Hertz, Marconi, and others. Radio, television, radar, microwave ovens, wireless computer networks, cell phones, keyless car door systems, wireless computer mice, systems for tracking wildlife and criminals, and on and on—the list of technologies using electromagnetic waves is long and growing with each passing day.

Outline

- I. The laws of physics exhibit a beautiful symmetry: Not only does a changing magnetic field produce an electric field, but as first recognized by James Clerk Maxwell in the 1860s, a changing electric field produces a magnetic field. The four fundamental laws of electromagnetism are named *Maxwell's equations* in Maxwell's honor. This is not a mathematical course, but everyone should see these equations at least once!

- A. Maxwell realized that the interplay of changing electric and magnetic fields, each regenerating the other, would result in an *electromagnetic wave*, which would propagate through space.
1. The speed of the waves was set by the two fundamental constants that appear in the laws of electromagnetism. When Maxwell calculated that speed, he found it to be the known speed of light.
 2. Maxwell concluded that light must be an electromagnetic wave, and in this single stroke of genius, he unified the sciences of optics and electromagnetism.
- B. The structure of an electromagnetic wave (at least in vacuum or in simple materials, such as air and glass) consists of electric and magnetic fields that are oriented at right angles to each other and to the direction of the wave's propagation.
- C. Like all other waves (recall Lecture Three), electromagnetic waves can be characterized by their wavelength and frequency. The two are not independent but multiply together to give the wave speed. Electromagnetic waves include radio, infrared, visible light, ultraviolet light, x-rays, and gamma rays. All are, in essence, the same. They differ only in frequency and wavelength—although that makes a big difference in how they interact with matter. (They also differ in a way determined by quantum physics, but we won't get into that here.) Together, the range of electromagnetic waves constitutes the *electromagnetic spectrum*.
- D. Electromagnetic waves can also differ in the direction of their electric field. This property is called *polarization*. Some sunglasses reduce glare by passing only one direction of polarization. The light that reflects off highways and other surfaces is polarized in the direction that doesn't pass; thus, the glare associated with such reflection is reduced.
- E. The behaviors of light described in Module One ultimately result from the interaction of the electric fields (and, to a much lesser extent, the magnetic fields) of electromagnetic waves with the electric charges that make up matter. A cosmic example: When the Universe was younger than about 500,000 years, it was so hot that individual atoms couldn't stick together. For this reason, the early Universe consisted of a gas of mostly electrons and protons. Because these individual particles are charged, they interacted strongly with electromagnetic waves, absorbing the waves' energy. Thus, the early Universe was opaque. At about 500 million years, atoms formed. Because atoms are electrically neutral, they interact less with electromagnetic waves. Thus, the Universe became transparent, and waves present then were unlikely to interact much with matter. Today, we see those waves as the *cosmic microwave background*, a kind of electromagnetic "fossil" that carries a rich array of information about the early Universe.

- II. Making electromagnetic waves is, in principle, as simple as setting an electric charge or a magnet into accelerated motion. Uniform motion is not enough to make the changing fields that regenerate each other (those who have studied relativity will see why); accelerated motion is required. In practice, the means to generate electromagnetic waves efficiently depends on the wavelength of the waves being produced.
- A. As a rule of thumb, a system involving accelerating charges becomes an effective producer of electromagnetic waves when the size of the system approaches the wavelength of the waves. At higher frequency (shorter wavelength), a system can, therefore, be smaller and still be an effective producer of electromagnetic waves.
1. This explains why radio waves come from fairly large engineered systems (antennas); why infrared comes, often, from molecules and visible light, from the outer electrons of individual atoms; why x-rays involve the innermost atomic electrons; and why gamma rays are emitted in nuclear interactions.
 2. Going back to Lecture Five, this also provides a deeper explanation for why the sky is blue. The atmospheric molecules that interact with sunlight are closer in size to (but still considerably smaller than) the wavelength of blue light than of red light. The molecules absorb light energy and vibrate, again emitting electromagnetic waves. But they're more effective emitters for the shorter wavelength blue light, which scatters about in the atmosphere and gives the sky its blue color.
- B. Radio waves (including television, microwaves, radar, wireless phones, and so on) are usually produced and received with *antennas*. These are generally systems of electrical conductors, sized typically between one-fourth of the wavelength of the waves to a full wavelength. For transmitting, an alternating current at the wave frequency is sent into the antenna. The back-and-forth motion of the electrons in the antenna is the accelerated motion that produces electromagnetic waves. For receiving, the electric field of the wave excites an alternating current in the antenna, which is amplified by the radio or TV receiver.
1. A simple antenna consists of a couple of lengths of conductor, totaling a half wavelength long. This system is most effective at receiving and sending signals at right angles to its length, because then, the wave's electric field can be parallel to the conductor. That's why reorienting an antenna often helps with reception.
 2. Another approach to producing short-wavelength radio waves (microwaves) is to whirl electrons around in a circle under the influence of a magnetic force. The *magnetron* in your microwave oven does just this, with electrons whirling about 2.4 billion times a second to produce microwaves with a frequency of 2.4 billion cycles per second (2.4 gigahertz) and a corresponding wavelength

of about 5 inches. (This frequency is also used by some cordless phones and wireless computer networks, which is why a microwave oven can interfere with these devices.)

C. Atoms and molecules are in constant vibrational motion because of the energy associated with what we call, loosely, heat (more on heat and a more precise definition in Lecture Twenty-Five). The associated acceleration of electric charge produces a broad range of electromagnetic waves whose frequency depends on the temperature. A very hot object, such as the Sun, produces mostly visible light. A glowing stove burner produces mostly infrared, along with some red light. Earth itself produces longer wavelength infrared, which plays a major role in global warming. The Universe itself is, on average, so cool that it “glows” with microwaves that provide clues to its origin and structure. Some astrophysical objects, in contrast, are so hot that they “glow” with x-rays.

D. Other processes that accelerate electric charge also result in electromagnetic waves. In a medical x-ray unit, for example, electrons are accelerated to high speeds with a steady electric field. They then slam into a very hard target made from tungsten. Their abrupt stopping constitutes the acceleration that generates electromagnetic waves. This stopping takes a very short time, which makes the frequency of the waves so high that they’re in the x-ray region of the spectrum.

III. Electromagnetic waves carry energy. That’s how the energy that runs our planet gets from Sun to Earth. But they also carry momentum and exert forces on objects. That force is negligible in most terrestrial applications, but it can be important in astrophysical systems, and it has been proposed as a propulsion force for interplanetary and even interstellar spacecraft that would be accelerated by the force of light on a huge, reflective sail.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 26 through p. 502.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 16, section 1.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 34.

Questions to Consider:

1. Only the lowest frequency electromagnetic waves penetrate seawater. To communicate with submerged submarines requires antennas hundreds of miles long. Why?

2. Is there a sharp distinction between infrared and visible light? Between microwaves and infrared? Between ultraviolet and x-rays? Why or why not?

Module Four: From Atom to Computer

Lecture Nineteen

The Miracle Element

Scope: “Physics in your life” isn’t just low-tech physics. Electronic devices, based on semiconductor technology, are ubiquitous in our lives. Increasingly pervasive are digital computers, which include not only our obvious personal computers but, increasingly, any number of “smart” devices from cars to thermostats to phones that all contain tiny computers. Ultimately, the workings of these devices are based in the nature of the atom.

This first lecture in Module Four introduces silicon, the “miracle element” at the heart of modern electronics. Silicon is one of a class of substances called *semiconductors* whose electrical properties lie between those of insulators and normal conductors, such as metals. We have learned to manipulate the electrical properties of semiconductors with exquisite precision, and that manipulation enables the myriad semiconductor devices, from individual transistors to computer chips, that enable our electronic technology.

Outline

- I. *Semiconductors* are a class of materials whose ability to conduct electricity lies between that of essentially nonconducting insulators, on the one hand, and the metals and other good conductors, on the other hand.
 - A. Although there is a wide range of semiconductor materials, both among the chemical elements and among synthesized compounds, the most important by far is the element silicon. Remarkably, silicon is not some rare, exotic material, but is the second most common element on Earth, after oxygen. Ordinary sand is largely silicon dioxide (SiO_2), as are quartz and most glass.
 - B. In the solid state, silicon and other semiconductors form crystal structures in which individual atoms bond to each other by sharing their outermost electrons (covalent bonds; Lecture Thirteen). In this way, semiconductors are like insulators, in which all the outer electrons are locked into the interatomic bonds and are not free to carry electric current. In metals, in contrast, atoms contribute their outermost electrons to a “sea” of free electrons that can carry electric current.
 1. Silicon atoms have four outermost electrons that participate in the interatomic bonds. A simplified, two-dimensional model of a silicon crystal shows each atom bonded to its four nearest neighbors. Two electrons join each pair of atoms, so these are

double bonds. (The silicon atoms actually bond in three dimensions, with a tetrahedral structure.)

2. At very low temperatures, all the electrons are locked into these bonds, so there are no electrons free to carry electric current. The silicon is an insulator.
3. At normal temperatures, the atoms in the crystal vibrate slightly in the random motion we call, loosely, heat. Occasionally, this thermal energy is enough to free an electron from an interatomic bond. The electron then wanders freely throughout the crystal. Applying a voltage across the silicon crystal produces an electric field that causes the free electrons to move in response, making an electric current. The silicon has become an electrical conductor, albeit a rather poor one.
4. The broken bond, with its electron missing, constitutes a *hole*. Because it’s a place where an electron is missing from a structure that was, overall, electrically neutral, the hole acts like a local region of positive electric charge. It’s possible for an electron from a nearby bond to leave its bond and take the place of the missing electron, “falling” into the “hole.” In this way, the hole can move throughout the crystal. If a voltage is applied to the crystal, electrons will be encouraged to move into nearby holes, with the effect that the holes, acting like positive charges, move through the crystal, making an electric current.
5. There’s a big difference, then, between semiconductors and ordinary metallic conductors. In metals, electrons alone carry the electric current. But in a semiconductor, electric current is carried by negative electrons and positive holes. For every electron that’s freed from an interatomic bond in pure silicon, a hole is also created. That there are two kinds of current carriers in semiconductors is what gives these materials their immense usefulness.
 - C. In pure silicon, there are equal numbers of electrons and holes contributing to the material’s electrical conductivity. At room temperature, pure silicon is a modest electrical conductor but not particularly useful or interesting. Pure semiconductors, also called *intrinsic semiconductors*, have little application in mainstream electronic devices, but they do have a few significant uses.
 1. Because electrons are freed from interatomic bonds by thermal agitation, the number of electron-hole pairs increases with increasing temperature. Thus, intrinsic semiconductors become better conductors at higher temperatures. Equivalently, the electrical resistance of a piece of intrinsic semiconductor decreases with increasing temperature.
 2. A *thermistor* is a piece of intrinsic semiconductor engineered so its temperature-dependent electrical resistance serves to measure

temperature. Thermistors are widely used in such everyday devices as fever thermometers, automobile temperature gauges, and household thermostats.

3. Intrinsic semiconductors are also used in some radiation detectors, in which incoming radiation creates electron-hole pairs, resulting in an electrical signal that not only detects the radiation but also provides a measure of its energy.

II. The vast majority of semiconductor applications involve *extrinsic* or *doped* semiconductors—semiconductor materials that have been deliberately “doped” or contaminated with other substances.

A. Atoms of some elements—arsenic, for example—have five outermost electrons that can participate in interatomic bonding, in contrast to silicon’s four. If an occasional arsenic atom is introduced into a silicon crystal, the arsenic can “fit” into the crystal structure, bonding like silicon would to its four nearest neighbors. But the fifth electron is extra and can’t participate in the bonding. It’s free to wander throughout the material and, in response to an applied voltage, to participate in carrying electric current.

1. Even a very low level of such doping can add a great many free electrons, making the doped silicon a much better conductor. Typical doping levels are around 1 arsenic atom for every 10 million silicon atoms. The reason doping is so effective is that there are so few electron-hole pairs formed by thermal agitation in pure silicon. With doping, we get much better conduction and, importantly, precise control over the electrical properties of the doped materials.
2. The vast majority of free charges in the arsenic-doped silicon are electrons. Because electrons carry negative charge, this particular doped silicon is called an *N-type semiconductor*. The *N* doesn’t mean the material itself is negatively charged—it’s still electrically neutral—but that the charges that are free to move in the material are negative.

B. Other atoms—aluminum, for example—have only three outermost electrons. The occasional aluminum atom can fit into the silicon crystal, but then there aren’t enough electrons to complete all the bonds with neighbor atoms. The missing bond is a “hole” into which an electron from a nearby bond can “fall.” In this way, the hole can move throughout the crystal. Because it is the absence of an electron, the hole acts like a positive charge.

1. Even a very low level of doping with aluminum or a similar material “floods” the silicon crystal with holes that act as positive charge carriers. Again, the silicon becomes a much better conductor than it would be without doping.

2. The vast majority of free charges in the aluminum-doped silicon are holes. Because they act as positive charges, this doped silicon is called a *P-type semiconductor*. Again, the *P* doesn’t mean the material itself is positively charged—it’s still electrically neutral—but that the charges in the material that are free to move are positive.

III. Quantum physics provides another way to understand semiconductors.

- A.** Quantum physics shows that electrons in atoms can have only certain discrete energies. It takes energy to “promote” an electron to a higher level, and energy is released when an electron “falls” from a higher level to a lower.
- B.** Only two electrons can occupy a given energy level (and the two must have their *spins* in opposite directions). If an energy level is full, then additional electrons can’t be promoted or fall into that level.
- C.** When two atoms combine to make molecules, individual energy levels split to make a more complex structure of molecular energy levels. This is most significant with the outermost levels, whose electrons “feel” and interact with those of the other atom.
- D.** When multiple atoms combine to make a crystal, each level becomes a nearly continuous band of allowed electron energies, separated by *energy gaps*.
- E.** The distribution of electrons in the outermost bands determines whether a material is an electrical conductor, an insulator, or a semiconductor.
 1. In a conductor, the highest energy band that electrons normally occupy is only partially full. Electrons can be promoted to adjacent levels in the band with very little energy. That’s why the electrons in a conductor respond readily to applied voltages, resulting in the flow of current.
 2. In an insulator, the highest energy occupied band is completely full of electrons. There are no nearby energy levels, and the minimum energy an electron could gain is the large energy of the band gap. Because this is very unlikely, the material has essentially no electrons that are free to move, and it can’t conduct electric current.
 3. A semiconductor is similar to an insulator, and at very low temperatures, it becomes an insulator. But the band gap in a semiconductor is very small, so at normal temperatures, some electrons have enough energy to jump the gap, where they then occupy a partially filled band like a conductor’s. This is what gives the material its slight electrical conductivity.
 4. Doping a semiconductor—adding the small amounts of impurities that we already saw led to increases in the number of electrons or holes—introduces new energy levels that either donate electrons to the empty band or produce holes by accepting electrons from a

nearly filled band. The result is an N-type or a P-type semiconductor, respectively.

- IV. It's the existence of two complementary types of semiconductor—P and N—that makes possible nearly all the devices used in semiconductor electronics. Although there are always a few *minority charge carriers* present because of electron-hole pairs created by thermal agitation, the electrical properties of each type of material are dominated by the *majority carriers*—the electrons or holes contributed by the doping material.

Suggested Reading:

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 21, section 3, pp. 452–453.

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 27, p. 694.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 42, section 3 (a quantum description of semiconductors).

Questions to Consider:

1. Doping silicon with arsenic produces an N-type semiconductor, with each arsenic atom contributing a free electron. How is it that the material remains overall electrically neutral despite all those free electrons?
2. Is a semiconductor more like an insulator or a metallic conductor? Does your answer depend on any other conditions?

Lecture Twenty

The Twentieth Century's Greatest Invention?

Scope: The 20th century saw unprecedented technological advances, with major inventions in areas ranging from medicine to agriculture, to space flight, to optics, to mechanics, to electronics. Near the top of virtually every list of the most important inventions of the 20th century is the transistor, a tiny semiconductor device at the heart of every electronic gadget from the simplest radio to the most complex supercomputer. The transistor's secret is that it lets one electrical circuit control another. The transistor, and its simpler cousin, the diode, are created in the conjunction of the two types of semiconductor, N and P, and depend for their operation on the remarkable properties of the PN junction.

Outline

- I. A *PN junction* forms at the interface where a piece of P-type semiconductor is joined to a piece of N-type semiconductor.
 - A. In the common process of *diffusion*, a material tends to move from a region of high concentration to a region of lower concentration. Open a bottle of perfume, for example, and perfume molecules diffuse from the bottle and eventually reach the far corners of the room. There's no magic here; it's just that there are more molecules in the region of high concentration, and they're moving in random directions. Thus, there are more molecules moving away from the region of high concentration than there are moving toward that region.
 - B. When P and N semiconductors are first brought together, there is a high concentration of holes in the P-type material and a high concentration of electrons in the N-type. Thus, each type of charge carrier diffuses across the junction. Electrons diffusing into the P-type material "fall" into the holes they find there, reducing the number of free charges just on the P side of the junction. Holes diffusing into the N-type material encounter electrons; again, electrons and holes recombine. The result is a dearth of free charges in the region near the junction, and as a result, the junction region becomes a very poor conductor and a barrier to the flow of electric current. Because it's been depleted of free charges, the region around the junction is called the *depletion region*.
 - C. Because the P- and N-type semiconductors were initially electrically neutral, diffusion of positive holes into the N-type material gives that material a net positive charge in the region of the junction. Similarly, electrons diffusing into the P-type material give it a slight negative charge. Eventually, enough charge builds up to repel additional electrons trying to diffuse into the P-type material and holes into the N-

type material. As a result, a balance is established between diffusion and electric repulsion. This balance develops almost immediately after the PN junction forms.

- D. If a battery is connected to the P and N materials, with the battery's positive terminal to the N-type material, the effect is to widen the depletion region and strengthen the electric field, making the junction an even poorer conductor. This condition is called *reverse bias*.
 - E. But connect the battery with its positive terminal to the P-type material, and the depletion region shrinks. The junction becomes a decent conductor, and current can flow through the device from P to N.
 - F. All this sounds complicated, but it boils down to one simple fact: A PN junction conducts electricity in one direction but not the other. It conducts when its P-type side is made more positive and the N-type side is made negative. It doesn't conduct in the opposite case. That's all we need to know from now on.
- II. Joining P- and N-type materials makes a *diode*, a useful device in its own right.
- A. Diodes act as one-way valves for electric current and are, therefore, used to convert alternating current (AC) to direct current (DC). Because virtually all electronic equipment uses DC, diodes are ubiquitous in electronic devices powered by regular AC household wiring.
 - B. In a diode that's conducting current, electrons and holes are continually recombining at the junction. Energy is released when an electron "falls" into a hole. In *light-emitting diodes (LEDs)*, the semiconductor materials are engineered to have an energy band gap such that the energy is released as visible (or sometimes infrared) light. Most of the small red and green lights used as indicators in electrical equipment are LEDs, because they're more energy efficient and far longer lasting than traditional lightbulbs. High-intensity LEDs are now available in flashlights and other applications, and it is only a matter of time before they replace lightbulbs in most everyday lighting applications.
 - C. The reverse process can occur, too. In a *photovoltaic (PV) cell*, incoming light energy dislodges electrons, creating electron-hole pairs (recall Lecture Sixteen). When these pairs form near a PN junction, electrons move into the N-type material and holes into the P-type material under the influence of the electric field established at the junction. As a result, the N-type material becomes negatively charged and the P-type material becomes positively charged. Connecting an external circuit allows current to flow, delivering electrical energy. Thus, the PV cell converts solar energy into electrical energy. One trick in making efficient PV cells is to utilize different materials whose band gaps correspond to different energies in the solar spectrum.

- III. A *transistor* is a device containing two PN junctions, which allows one electric circuit to control another. There are many types of transistors, but the easiest to understand is the *field-effect transistor (FET)*, widely used in computers and other electronic devices. The particular transistor I'll describe is a *metal-oxide-semiconductor field-effect transistor (MOSFET)*.
- A. In a common type of FET, two pieces of N-type semiconductor are embedded in a block of P-type material.
 - B. If a battery is connected via the wires attached to the N-type pieces, no matter which to the positive battery terminal and which to the negative, no current flows. That's because there are two PN junctions where the N-type pieces join the P-type, and no matter how the battery is connected, one of these will always be connected in the way that blocks current.
 - C. There's more to the transistor. A thin layer of insulating material (usually silicon dioxide, made by exposing the silicon block to oxygen) is formed over the P-type "channel" between the N-type pieces, and a layer of metal is coated on top of the insulator. If the metal (called the *gate*) is connected to the positive terminal of a battery, it becomes positively charged, repelling holes and attracting electrons into the material below it. Even though the material has been doped to be P-type, the influx of electrons makes it temporarily N-type. Now, the PN junctions are temporarily gone, and there's no barrier to current flow between the two N-type pieces. The transistor has become a conductor.
 - 1. How good a conductor it is can be controlled by the amount of charge on the gate, which is determined by the voltage applied to the gate. Thus, the gate voltage controls the current through the transistor. A very weak electrical signal at the gate can control a much larger one, making the transistor an *amplifier*. Amplifiers are used throughout audio and video electronics to boost the level of electrical signals from microphones, CD pickups, tape heads, and so forth.
 - 2. The transistor can also be operated in a mode where the gate voltage swings between two extremes, making the device behave like a switch that is either on or off. In this mode, the transistor forms the heart of digital electronic devices.
 - 3. It's possible to build a complementary transistor, with P-type material embedded in an N-type block. The use of complementary transistors enables energy-efficient circuitry ranging from laptop computers to high-power audio amplifiers.

Suggested Reading:

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction to Physics*, chapter 21, section 3, pp. 453–455 (Griffith describes a different type of transistor).

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 27, pp. 695–696.

Going Deeper:

Neil Storey, *Electronics: A Systems Approach*, chapter 5.

Paul Horowitz and Winfield Hill, *The Art of Electronics*, chapter 2.

Questions to Consider:

1. How is a diode like a one-way street?
2. In a lightbulb, current flowing through the bulb's filament heats the filament until it glows. In a light-emitting diode (LED), current flowing through the device results in electrons and holes recombining, producing visible light in the process. Why might an LED be more efficient than a lightbulb in converting electrical energy to light?

Lecture Twenty-One

Building the Electronics Revolution

Scope: Transistors, invented in the 1950s, were a great improvement over their predecessors, vacuum tubes. But it was still tedious to connect individual transistors into a circuit that performed a useful function. The revolution that enabled modern electronics came in the early 1960s, when engineers learned to combine multiple transistors and other electronic devices on a single piece, or *chip*, of silicon. The first such *integrated circuits* contained only two transistors. By 1965, the number of transistors on an integrated circuit had increased to about 100, which prompted Gordon Moore to propose *Moore's law*, stating that the number of transistors per integrated circuit would grow exponentially, doubling each year or two. Moore's law has now held for more than four decades, and today's most advanced integrated circuits contain a billion transistors. Each transistor is smaller than an influenza virus! Not only are transistors getting smaller and more densely packed, but they're also getting faster at switching from the conducting to the nonconducting state, enabling ever-faster computers. That's why the new computer you bought last year is already obsolete!

Eventually, the continuing miniaturization of semiconductor electronics will run into fundamental limitations set by quantum physics. Some startling alternatives are already in the works.

Outline

- I. Transistors aren't the first devices that use one electric circuit to control another.
 - A. *Electromechanical relays* use an electromagnet to operate a mechanical switch. The current to the electromagnet thus controls the current through the switch. Relays are heavy, expensive, and slow.
 - B. *Vacuum tubes*, invented in the early 20th century, control the flow of electrons in an evacuated glass tube. They contain a hot filament, similar to a lightbulb's, to provide a source of electrons. Tubes are large, bulky, and fragile; consume a lot of power; and burn out frequently.
 1. One of the first electronic computers, ENIAC (Electronic Numerical Integrator and Computer, 1946), contained some 19,000 vacuum tubes and more than 1,000 relays. It filled an entire room and consumed electrical energy at the rate of 200,000 watts. Yet its computing power was far less than the smallest of today's personal computers.

2. Although vacuum tubes have been largely superseded by transistors, they are still used in some specialized applications, including high-power radio transmitters and microwave sources. Some audiophiles prefer tube amplifiers. And the “picture tube,” a specialized vacuum tube, is still used for video display in television and computer monitors—although that is rapidly changing.
- II.** Transistors are a great improvement over vacuum tubes, being small, robust, long lasting, and low in power consumption. However, the electronics revolution is fueled not by individual transistors but by our ability to pack thousands, millions, and even billions of transistors on a single “chip” of silicon.
- A. The first *integrated circuits*, developed in the late 1950s, contained only a few transistors, other electronic components, and the electrical conductors that joined them into a useful circuit. Although integrated-circuit design is now the province of engineers, physics is at the root of it: Jack S. Kilby of Texas Instruments shared the 2000 Nobel Prize in Physics for his role in the invention of the integrated circuit.
 - B. In 1965, Gordon Moore suggested that the number of transistors on a single integrated circuit would double roughly every year or two. *Moore’s law* has held through four decades, and today’s most advanced integrated circuits contain about a billion transistors. This is true exponential growth!
 - C. Linked with the increase in the number of transistors on a chip is an increase in the complexity of circuits that can be built and in the speed with which circuits carry out their functions—and a drop in price per transistor. That’s why your new, more powerful computer doesn’t cost any more than your old, obsolete one did.
 - D. Today, integrated circuits are ubiquitous. Specialized chips operate our cell phones, our children’s electronic toys, our DVD players, the digital controls on our washing machines and stoves, our robotic vacuum cleaners, our thermostats and home energy control systems, our cars’ fuel and pollution control systems. Chips implanted under our pets’ skin identify lost dogs and cats. Heart pacemakers contain chips that can be reprogrammed as the patient’s needs change. Increasingly, formerly mundane devices become “smart” with the addition of specialized integrated circuit chips. And, of course, our computers are full of chips.
- III.** Manufacture of integrated circuits involves some of the most technologically advanced equipment and procedures. Ultra-pure materials and the utmost cleanliness are essential for high yields of reliable circuits.
- A. Chip manufacture begins with the preparation of pure silicon crystals.
 1. Pure elemental silicon (produced from sand) is melted in a furnace. A carefully prepared “seed” crystal is lowered into the molten

silicon, then withdrawn at a precise rate while being rotated. Silicon crystallizes on the seed and the growing crystal as it’s removed from the melt. The result is a long cylindrical ingot of pure silicon.

2. The ingots are sawed into thin wafers, up to about a foot in diameter. The wafers are polished to make them perfectly flat. Lots of waste here!

- B.** A variety of processes are used to dope the silicon, making regions of P- and N-type silicon to form transistors, other electronic components, and their electrical interconnections. Most of this work is based in *photolithography*.
1. A typical process starts with the growth of a thin layer of ultra-pure silicon on the wafer—even purer than the wafer crystal itself. (Remember from Lecture Nineteen how dramatically contaminants affect the electrical characteristics of the silicon.)
 2. The wafer is heated and exposed to oxygen. This adds a thin layer of silicon dioxide. The silicon dioxide layer is coated with a light-sensitive material called *photoresist*.
 3. A mask is prepared, typically with a laser beam or electron beam etching a metal coating off a plate of high-quality glass. The mask outlines features on what will be one of many layers in the finished chip.
 4. Light is shined through the mask, exposing regions of the photoresist. As Moore’s law shrinks the size of individual circuit elements, the wavelength of the light needed to transfer patterns to the silicon wafer shrinks, too. Today’s high-tech chips feature transistors less than 1/10 of a micron across, much smaller than the wavelength of visible light. As a result, modern chip-making processes must use ultraviolet light, usually from excimer lasers similar to those used in laser vision correction. Typically, a wafer can hold several hundred identical integrated circuits; thus, the mask is stepped repeatedly over the wafer to produce multiple circuits.
 5. When the photoresist is developed, it leaves a layer over those regions that were exposed to light. An acid is then used to etch away the oxide layer. Exposure to a gas or beam of dopant atoms then creates the desired P or N type of semiconductor in exposed regions. The process is repeated to make additional layers that complete transistors and interconnect them to form the integrated circuit.
 6. Individual circuits are tested, then cut from the wafer, then mounted in sealed packages for insertion onto printed circuit boards.

IV. Eventually, the uncertainty principle of quantum physics will impose a lower limit on the size of conventional transistors. The future will probably require alternative technologies to perform the functions of today's semiconductor electronics.

A. Beyond that scale, *quantum computing*, which actually exploits ambiguity at the subatomic scale, may enable even greater advances in computing speed and power.

B. Researchers are also experimenting with "circuits" that use biological materials, such as DNA, to carry out computational operations. Tiny "DNA computers" might be placed inside biological cells for monitoring and control of cell functions. DNA computing has developed to the point where DNA-based computers can solve simple computational problems, thus raising the prospect of general-purpose computers based in molecular technology at much smaller scales than the current silicon technology.

V. Pause and consolidate: We're on a hierarchical journey from atom to computer. With each step, we "hide" the next lower level of complexity in a single symbol.

A. Starting with the atomic structure of a silicon crystal, we developed P- and N-type semiconductors. They show up symbolically as reddish and bluish colored blocks, respectively, in diagrams of PN junctions and transistors.

B. Now, we've seen how to put millions or even billions of transistors on a single chip of silicon; thus, a picture of a completed chip becomes our highest level symbol.

C. What we haven't done is to connect the transistors together in a meaningful way. That's what comes next.

Suggested Reading:

Scientific American, fall 1997, special issue: "The Solid-State Century."

Going Deeper:

Altan Ferendeci, *Physical Foundations of Solid State and Electron Devices*.

Questions to Consider:

1. The maximum number of transistors on an integrated circuit went from about 1,000 in 1970 to about a billion in 2005. Given this growth, roughly what is the time needed to double the number of transistors?
2. At the start of the 21st century, the most advanced integrated-circuit manufacturing involved features—such as individual transistors—about 130 nanometers in size (1 nanometer is one-billionth of a meter). By mid-decade, that had been reduced to 90 nanometers. At roughly the same time,

standard silicon wafers went from 8 inches in diameter to 12 inches in diameter. By what percentage did both changes together increase the number of integrated circuits that could fit on a wafer? Assume—incorrectly—no increase in circuit complexity.

Lecture Twenty-Two

Circuits—So Logical!

Scope: It takes just a few transistors to make circuits that perform simple logic functions. Such circuits are the building blocks of all digital electronics, including computers. Digital circuits store and process information in the form of binary numbers—sequences of ones and zeros in which each *bit* conveys a single piece of “either/or” information: on or off, one or zero, yes or no, high or low, true or false... The fundamental building blocks of computers are circuits that operate on such binary information, giving answers to such questions as “Are these two bits both 1?” or “Is either of these bits a 1?” and performing simple operations, such as changing a 1 to a 0 and vice versa. From multiple applications of such basic operations comes all the complex information processing that we expect from computers.

Outline

- I. There’s a hierarchy of ways to know and use computers.
 - A. Everyday users are often unaware that they’re using computers. Driving a car, where computers control the fuel system and the antilock brakes, is one example, as is using an automatic teller machine or a digital camera.
 - B. Most of us use “canned” computer programs, such as word processing programs, spreadsheets, and email programs, to make our computers do useful tasks.
 - C. Programming languages allow computer programmers to write the sequences of instructions that constitute useful programs. Programming languages range from very high level languages, in which a single command results in a powerful sequence of computer actions, to low-level languages that correspond to the limited number of simple, basic instructions that are “hard wired” into the computer’s circuits. In the middle of this range are such languages as JAVA, C, BASIC, and FORTRAN, used by programmers to create higher level programs and by scientists to create everything from spacecraft guidance programs to global climate models. Many “canned” programs have some programming capability, as well.
- II. At the most basic level, all that computers do is simple manipulations of binary numbers, which may represent actual numbers or text or other symbolic information. In the 32-bit personal computers of the late 1990s and early 2000s, those numbers contain 32 bits (binary digits). Newer computers use 64-bit numbers. More complex tasks—searching for a word in a document, removing “red eye” in a digital photo, calculating a spreadsheet,

checking an email for spam or virus—are ultimately combinations of simpler tasks. Here, we’ll start with the basics and build up to see how a computer can test two binary numbers to determine if they’re equal. A bit of glossary: A group of eight binary digits is called a *byte*.

- A. All digital information processing boils down to three simple logical functions on the binary digits 1 and 0 (which, again, can be interpreted to mean yes or no, true or false, and so on). These functions take one or two input values (either 1 or 0) and give a single output value (either 1 or 0).
 1. The *AND* operation gives an output of 1 only if both its inputs are 1. Call the inputs A and B; then, the output is 1 only if A AND B are both 1. The operation can be described logically by its *truth table*. Any circuit or device that performs this logic function is called an *AND gate*. Regardless of how they’re physically constructed, all AND gates are represented by a common symbol. A crude way to implement an AND gate is with hand-operated switches, a lightbulb, and a battery. The switches are connected one after the other (in series). If a closed switch and a lit bulb stand for logical 1, then only when both switches are closed does the lamp light.
 2. An *OR gate* gives an output of 1 if either input is 1—that is, if input A OR B is 1. Putting the switches in parallel turns our lightbulb circuit into an OR gate.
 3. The *NOT*, or *invert*, operation turns a 1 into a 0 and vice versa. Implementing a lightbulb NOT gate is also easy, although we need to add a *resistor*—just an electrical conductor that isn’t perfect—to keep too much current from flowing through the switch when it’s closed.
 4. In practice, it’s more convenient to make and to work with *NAND* (NOT AND) and *NOR* (NOT OR) gates, whose outputs are opposite those of the AND and OR gates. Connecting the two inputs of either gate together gives a NOT gate, which means that we really only need NAND and NOR to build all possible logic circuits. (In fact, we really need only one of these types.)
 5. Implementing NAND and NOR with transistors is easy. We’ll dispense with the lightbulb and take the voltage at a battery’s positive terminal to signify 1 and the voltage at the negative terminal to signify 0. In practice, computer circuits are almost this simple, but they use a few more transistors and avoid the resistor, that way consuming much less power.
 6. Equipped with NAND and NOR gates (and NOT gates, which can be made from either of the others), we have essentially everything that’s needed to build a computer. From now on, we’ll stop thinking about individual transistors and just work with logic symbols.

B. One of the many simple instructions a computer can execute is to compare two binary numbers to see whether or not they are equal. These might represent actual numbers, or they might represent text, coded as ASCII, where each character is an 8-bit byte. A search for a particular word in a text document, for example, tests each word in the text using a character-by-character comparison that is ultimately a test for equality of two binary numbers. We want a circuit that takes two binary numbers as its input and produces an output whose value is 1 only if the inputs are equal. We'll build gradually to that circuit.

1. With our basic gates, we can make the *exclusive OR* function, whose output is 1 if either of its inputs is 1 but not both. Here, we use four NAND gates. We can confirm that this works by constructing the truth table. This circuit also forms the heart of a binary adder, as well as of our equality tester. It's so useful that we'll give the circuit its own symbol.
2. Combining the outputs of several XOR gates through a NOR gate gives us our equality tester.
3. We'd like to test pairs of binary numbers with more than two bits each. That's easy; we add an XOR gate for each additional bit and feed the outputs into a multiple-input NOR gate—made from transistors just like our two-input NOR gate but with additional transistors connected in parallel. The video shows one that compares two 8-bit numbers, which could represent two alphabetic characters in ASCII code.

C. The equality tester is one of many circuits that execute simple instructions inside a computer. All are built from the basic logic gates, themselves built from transistors, which are made from P- and N-type semiconductors, which are ultimately made of atoms arranged into crystal structures with carefully engineered amounts of impurities added.

Suggested Reading:

Marshall Brain, *Marshall Brain's How Stuff Works*, pp. 112–113 (“How Bytes and Bits Work”).

Going Deeper:

Neil Storey, *Electronics: A Systems Approach*, chapter 9.

Paul Horowitz and Winfield Hill, *The Art of Electronics*, chapter 8 through p. 500.

Questions to Consider:

1. Design an exclusive OR circuit using only NOR gates instead of NAND gates (this can be done with just four gates).

2. Using logic gates with two inputs each, design a four-input AND gate—that is, a circuit that has four inputs and produces an output value that is 1 only if all four inputs are 1.
3. Show that you can make a circuit that provides the NOR function using only NAND gates and NOT gates (which you know can be made using NAND). Thus, you really need only one kind of gate to make all logic circuits.

Lecture Twenty-Three

How's Your Memory?

Scope: It isn't enough for a computer to be able to test for equality, to add, and to perform other simple operations on sequences of binary digits. It also needs to store the results and input data and to retrieve those stored items for further processing. That's the job of the computer's memory. Memory encompasses relatively slow but long-term storage media, such as magnetic tapes, optical discs (CD and DVD), and magnetic hard discs. But internal to the computer is the fastest memory, based in semiconductor electronics. The ongoing revolution in electronic miniaturization, as embodied in Moore's law, is behind today's computer memories that can store billions of bits of information. In this lecture, we see how individual memory cells work and how they're assembled into today's voluminous computer memories.

Outline

- I. Computers use a hierarchy of information storage systems; collectively, they can all be considered forms of *memory* because they "remember" the stored information.
 - A. As shown in Module One, optical discs (CD and DVD) provide inexpensive ways to store large amounts of digital information permanently. But they're relatively slow at transferring data, and most can be "written" only once. That's why most discs are considered *read-only memory (ROM)*.
 - B. Magnetic discs, as described in Module Three, store information in patterns of magnetization on a rapidly spinning disc. They have high storage capacity and moderate speed and can be rewritten indefinitely. They retain their information when the power is off. Typically, programs and data are stored on magnetic discs (hard discs) inside the computer until the programs and data are actually in use. Example: A word-processing program and a document normally "live" on your hard disc. When you "launch" a program, it's copied from the disc to faster, temporary memory. When you open a document, it, too, loads into that temporary memory.
 - C. *Semiconductor memory* is that temporary memory. It's fast, compact, and has no moving parts. It's relatively expensive, but Moore's law ensures that capacity will continue to increase even as cost drops. At some point, semiconductor memory will supersede magnetic disc storage.

1. Semiconductor memory is *random-access memory (RAM)*, meaning that any stored item can be accessed as quickly as any other.
 2. Semiconductor memory can be *volatile*, meaning that it loses the stored information when power is turned off, or *nonvolatile*, meaning that it stores information indefinitely. The main memory in a computer is generally fast, high-capacity, volatile RAM; that's why you can lose a lot of work if you haven't saved it (to the nonvolatile hard disc) when your computer crashes. Such devices as digital cameras, removable computer "pen drives," cards for video games, and similar applications use nonvolatile memory. Computers also contain nonvolatile memory that stores the information needed to get the computer started.
- II. Semiconductor memory ultimately uses transistors to store and/or transfer stored information.

A. *Static memory (SRAM, for static random-access memory)* stores information in the states of individual transistors or logic gates.

1. Connecting two NOT gates so the output of each gate goes to the input of the other gives a circuit that has two distinct stable states. If one gate's output is 1, then its input, which is the output of the other gate, must be 0. It doesn't matter which output is 1, but whichever is, then the other must be 0. Having both outputs simultaneously 0 or 1 is not possible. Because the circuit can be made to flip from one state to the other, it's called a *flip-flop*.
2. But how to flip the state? By making the flip-flop from NOR (or NAND) gates, we can control its state. Now we have two extra inputs. Normally, we'll keep them both in the 0 state. As the NOR truth table shows, that means each NOR gate's output will be 1 or 0, depending on whether its other input is, respectively, 0 or 1. We could have 1 at the output of the top gate or 0; either is fully consistent. Whatever value is stored in the circuit stays there.

Let's bring the lower input temporarily to 1. If the stored bit is 0, then the other input to the lower NOR gate is 0, and its output becomes 1. Now the upper NOR gate has both inputs 0, so its output—the stored bit—becomes 1. You can convince yourself that if the stored bit had been 1, it wouldn't have changed. Either way, we've ensured that the stored bit is 1. Drop the lower input back to 0, and there's no change, so bringing the lower NOR gate's free input momentarily to 1 makes the stored bit a 1. You can convince yourself that raising the upper NOR gate's free input forces the stored bit to 0.

What we have is a 1-bit memory! One of our inputs stores a 1 in the memory and the other stores a 0. We can determine the stored

value by seeing whether the output marked “stored bit” is in the 1 or 0 state.

- B.** The fastest memory is built from flip-flop circuits similar to, but a bit more complicated than, the one we just analyzed. However, this type of memory requires quite a bit of circuitry for each stored bit. For this reason, most computers use a slower but more economical type of memory, called *dynamic memory (DRAM, for dynamic random-access memory)*. In DRAM, each bit is stored as the presence (1) or absence (0) of electric charge on a pair of closely spaced electrical conductors built onto the integrated circuit. (Such an arrangement is called a *capacitor*.) A transistor controls the flow of charge to and from the capacitor, allowing the amount of charge to be changed (writing information) or sensed without change (reading the stored information). Unfortunately, the stored charge gradually leaks away; as a result, this type of memory has to be “refreshed,” typically several thousand times per second (hence the term *dynamic*). Although that sounds fast, it’s very slow on the time scales at which the computer operates.
- C.** Whatever kind of memory is used, individual 1-bit memory cells are arranged into 8-bit bytes and then into “words” of typically 4 or 8 bytes (32 or 64 bits). The cells are arranged in an array, connected to logic circuitry that allows individual words to be read (their stored values obtained for use elsewhere in the computer) or written (new information stored). One of the most important specifications for a computer is its total random-access memory (RAM), because that determines the size of the programs it can easily run or the files, such as large digital images, that it can process. A computer with 512 MB (megabyte) of RAM, for example, has approximately 512 million bytes of memory; one with 1 GB (gigabyte) has just over a billion bytes. (These numbers are approximate because computers work with binary numbers, and the size of memory is always an exact power of 2. Thus, 1 MB is exactly 2^{20} bytes, and 1 GB is 2^{30} bytes.)

III. Back to the big picture: We’ve now gone from atoms to something you can buy and put your hands on—namely, memory for your computer.

Suggested Reading:

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, pp. 478–482.

Marshall Brain, *Marshall Brain’s How Stuff Works*, pp. 117–125.

Going Deeper:

Neil Storey, *Electronics: A Systems Approach*, chapters 10–11.

Paul Horowitz and Winfield Hill, *The Art of Electronics*, chapter 8, pp. 500–516.

Questions to Consider:

1. In this lecture, we analyzed a 1-bit memory made from NOR gates. You can also make a memory if you replace the NOR gates with NAND gates. Analyze this memory, and show that you need to keep the inputs normally in the 1 state and set one or the other to 0 in order to store information in the memory.
2. Given that the number of bits in computer memory is always a power of 2, what is the exact size of a kilobyte (kB)? (*Kilo* means 1000.)

Lecture Twenty-Four

Atom to Computer

Scope: With one example of a processing circuit (the equality tester, Lecture Twenty-Two) and knowing how computer memory works (Lecture Twenty-Three), we're ready to put it all together to make a complete computer. Computers aren't just about numbers, however; they also process information, such as text and images. For this reason, we also need to understand how such information is coded into the binary language computers can understand. And we need to be able to get information into and out of our computer. Here, we look briefly at the overall structure of computers, how they encode text and other information, and their input and display devices.

Outline

- I. A complete computer comprises a processing unit; memory, including high-speed semiconductor RAM, a magnetic hard disc, and drives for optical discs; input devices, such as a keyboard and mouse; interfaces for connecting to the Internet; and a video display.
 - A. The *central processing unit (CPU)* (often called a *microprocessor* in personal computers) is at the heart of the computer. This unit contains circuits, like the equality tester we developed in Lecture Twenty-Two, that perform simple arithmetic or logic operations on binary numbers (the 32- or 64-bit "words" used in today's computers). The CPU also has limited but very high-speed temporary memory, called a *cache*, for storing instructions to be executed and data to be operated on. There are also special memory registers that keep track of the steps to be performed in a program, circuits that fetch and decode specific instructions, and a *clock* that generates electrical pulses at a regular rate to keep all the computer's actions happening in an ordered sequence.
 1. When you hear that a computer contains a "G5 chip" or a "Pentium chip," that's a description of the specific model of microprocessor used in the computer.
 2. The speed of the computer, usually expressed in gigahertz (GHz, or billions of Hertz), describes the rate of the CPU's internal clock; 1 Hertz is one clock pulse per second. Typically, a computer can perform the simplest tasks, such as fetching a word from memory or adding two numbers, in one to a few clock cycles. Thus, a 2-GHz computer (2 billion clock pulses per second) might take as little as half a billionth of a second to perform a simple task. Equivalently, it might perform as many as 2 billion such tasks each second. However, some CPUs have more complex circuitry that lets them perform several operations at once; for this reason, the

clock rate in GHz is not a reliable indicator of a computer's overall speed.

- B. The CPU is mounted on a *motherboard* that also contains the random-access memory and other integrated circuits. The board itself is made of insulating material like fiberglass or epoxy, with electrically conducting copper pathways connecting the integrated circuits. Modern motherboards are multilayer structures, allowing complex interconnections among the various integrated circuits. The motherboard is essentially the complete computer, minus long-term memory devices, such as hard drives, and input and display devices.
 1. The motherboard is characterized by the speed and width of its *data bus*—the name for the channel that carries digital data back and forth between the CPU, memory, and other devices. A 64-bit-wide bus carries 64 bits simultaneously. A modern high-performance data bus might have a width of 128 bits and can transfer hundreds of millions to a billion or more 128-bit chunks of data each second.
 2. Also on the motherboard are specialized integrated circuits that transfer data to and from hard discs, CD and DVD discs, and other data storage devices; circuits that communicate with input devices, such as the keyboard and mouse; circuits that format data and send it to output devices, including displays and printers; general-purpose interfaces, such as the universal serial bus (USB); and circuits for high-speed network connections. The motherboard usually has empty slots for additional memory or specialized purposes, allowing the computer to be customized.
 3. Communications between the motherboard and the outside world can be either *parallel* or *serial*. In parallel systems, large numbers of bits are transferred all at once. Parallel communication is very fast, but it requires large numbers of wires. In serial communication, bits are sent one at a time. Most peripheral devices, and all network communication, use serial data transfer.
- C. Input and output devices permit communication between the computer and a human being.
 1. A computer's keyboard is simply a set of switches arranged in a grid. Pressing a key causes electric current to flow on two wires that identify the key's horizontal and vertical locations in the grid. A built-in microprocessor identifies the key and transmits a code for the associated letter or other character to the computer. The microprocessor also identifies special key combinations, and it eliminates multiple keystrokes that might occur because of mechanical "bouncing" of switch contacts. Some keyboards use so-called capacitive switches, in which there is no actual electrical contact.

2. The first computer mouse was a simple device in which a rolling ball turned two perpendicular shafts whose rotations were detected optically. The mouse used most often today is entirely optical, bouncing light from a light-emitting diode off the surface on which the mouse is moving. The reflected light is detected by a sensor similar to that in a digital camera, and a tiny built-in microprocessor analyses the changing patterns to calculate the mouse's motion. That information is sent to the computer, which uses it to move the cursor on the display device.
 3. Modern computers generally use *liquid crystal displays (LCDs)*. In these devices, application of a voltage to individual picture elements, or *pixels*, alters the orientation of the molecules in a so-called liquid crystal. This, in turn, changes the polarization of light coming through the crystal and either blocks or allows passage of the light through a subsequent polarizing filter. Red, blue, and green color filters at each pixel allow combinations of colored light to give a full-color image. Touch-screen displays used in supermarket checkouts, information kiosks, and the like include a surface layer that detects the location of a finger touch, allowing the display to function as both an input and output device.
- II. Computers don't just compute:** They process all sorts of information, including text and images. Ultimately, though, that information is encoded as binary numbers.
- A. Each text character is encoded as a single 8-bit byte, as we saw briefly in the previous lecture. For example, the capital letter A is assigned the binary equivalent of the decimal number 65 (01000001); a blank space is the number 32, or 00100000 in binary; and the number 8 (00001000) is the backspace character. The word *text* is a sequence of four 8-bit bytes: 01010100 01000101 01011000 01010100. A document you just typed, or even the whole book you just read, has a similar representation as a sequence of binary bytes. (This coding is called the American Standard Code for Information Interchange, or ASCII; if you save a computer document as "ASCII text," you're storing just these codes, without a word processor's special formatting, such as bold or italic lettering.) Often the codes are written in base 8 (octal) or base 16 (hexadecimal) because they translate easily to base 2.
 - B. The binary representations of music and images require huge amounts of binary information. Each pixel in a digital image, for example, must be encoded as binary numbers representing the intensity and the color of the light. *Compression* techniques reduce the number of bits required without significantly altering the quality of the information. For example, movies can be compressed with the MPEG (for Motion Pictures Experts Group) scheme, which finds redundant pixels both within a given frame of the movie and in adjacent frames and eliminates

them in the stored data. The much smaller MPEG files are easily stored or transmitted over the Internet. The compressed images are "decompressed" to restore the missing information for display. Similarly, digital cameras often use JPEG (Joint Photographic Experts Group) compression, which can reduce a 15-million-byte image to fewer than 1 million bytes. And the notorious MP3 music format is really a compression scheme that extracts music from a CD and reduces the number of bytes by a factor of about 10. That's what allows easy swapping and storage of music files, much to the consternation of the recording industry. (MP3 is actually the audio portion of the MPEG movie compression scheme.)

III. Wrap-up of Module Four: We really have come all the way from atom to computer!

Suggested Reading:

Henry Fountain, *The New York Times Circuits: How Electronic Things Work*, pp. 36–77.

Marshall Brain, *Marshall Brain's How Stuff Works*, chapter 5.

Going Deeper:

Neil Storey, *Electronics: A Systems Approach*, chapter 12.

Paul Horowitz and Winfield Hill, *The Art of Electronics*, chapter 10.

Questions to Consider:

1. Look up the specifications for your own personal computer, finding (a) total RAM in megabytes or gigabytes; (b) hard-disc capacity in gigabytes; (c) microprocessor type; (d) clock rate in gigahertz; (e) bus width in bits; and (f) bus rate in megahertz or gigahertz. Explain what each means and what role it plays in establishing your computer's performance.
2. Suppose you have a 5-megapixel digital camera, meaning that the image sensor records information from 5 million different spots. In a typical camera, the intensity of each of the colors red, green, and blue at each pixel is encoded as a 24-bit binary number. Estimate the size, in bytes, of a "raw," uncompressed image from such a camera. Remember that there are 8 bits in a byte. No wonder compression is needed to get manageable file sizes!

Glossary

Aerodynamic lift: The upward force of air on an airplane or bird wing.

Ampere: The unit of electric current, equal to 1 coulomb of charge per second.

Amplifier: An electronic circuit that boosts either the voltage or current of an electrical signal.

Amplitude: The size of the disturbance that constitutes a wave.

AND: The logical operation whose output is 1 only if both inputs are 1.

Angular momentum: A measure of an object's rotational motion; the product of rotational inertia and angular velocity.

Angular velocity: A measure of the rotation rate of a rotating object.

Antenna: A system of electrical conductors used to send or receive electromagnetic waves.

Apparent weight: The "weight" read by a spring scale, which may or may not be your actual weight (the force that gravity exerts on you), depending on whether or not you're accelerating.

Apparent weightlessness: The condition encountered in any freely falling reference frame, such as an orbiting spacecraft, in which all objects have the same acceleration and, thus, seem weightless relative to their local environment.

Arteriosclerosis: A buildup of fatty plaque in the walls of arteries. Can lead to blockage or to collapse, as described by Bernoulli's principle.

Atomic number: The total number of protons in an atom's nucleus and, hence, the number of electrons in a neutral atom. Determines what element an atom belongs to.

Axons: Long extensions of neurons that carry signals to other neurons.

Battery: A device that converts chemical energy to electrical energy by separating positive and negative charge.

Beats: Sound heard at the frequency difference between two sound waves of very similar but not identical frequency.

Bernoulli's principle: A statement of energy conservation in a fluid, showing that the pressure is lowest where the flow speed is greatest and vice versa.

Big Bang: The explosive event that began the Universe as we know it.

Bit: A single binary digit, which can have only one of the two values 0 or 1.

Buoyancy force: The upward force on an object that is less dense than the surrounding fluid, resulting from greater pressure at the bottom of the object.

Byte: A sequence of 8 bits.

Cache: Special high-speed computer memory used for temporary storage of data and instructions.

Carnot engine: A simple engine that extracts energy from a hot medium and produces useful work. Its efficiency, which is less than 100 percent, is the highest possible for any heat engine.

CCD: See **charge-coupled device**.

Center of mass: A point where an object acts as though all its mass were concentrated.

Central processing unit (CPU): The main electronic circuitry of a computer, which performs fundamental operations on digital data.

Centrifugal force: There's no such thing! Banish this word from your vocabulary. See Lecture Nine.

Centripetal force: Any real, physical force that acts to keep an object moving in a circular path. Examples include gravity for the Moon and the friction of tires on the road for a car rounding a curve.

Charge-coupled device (CCD): A light detector that captures visual information using electrons in individual picture elements (pixels). Used in digital cameras and many other devices.

Chip: See **integrated circuit**.

Circular orbit: One of many possible paths for an orbiting object; in a circular orbit, the object remains at a fixed distance from the gravitating center and its speed remains constant.

Classical physics: The theories and descriptions of physical reality developed before about the year 1900, specifically excluding relativity and quantum physics.

Clock: A circuit inside a computer that generates a periodic signal used for synchronizing and timing all computer operations.

Cogeneration: The process of generating both usable thermal energy and electrical energy in the same power plant.

Collision: An intense interaction between objects that lasts a short time and involves very large forces.

Compression: A technique used to reduce the number of bits needed to store digital information.

Conduction: Heat transfer by physical contact.

Conductor: A material that contains electric charges that are free to move and can, thus, carry electric current.

Conservation-of-energy principle: The principle that energy cannot be created or destroyed, strictly valid in pre-relativity physics.

Conserved quantity: A quantity whose value does not change, at least in a given circumstance.

Constructive interference: See **interference**.

Convection: Heat transfer resulting from fluid motion.

Convection oven: An oven that uses forced circulation of hot air to reduce cooking time.

Cosmic microwave background: Electromagnetic radiation in the microwave region of the spectrum, which pervades the Universe and represents a “fossil” relic of the time when atoms first formed, about half a million years after the Big Bang.

Cosmological constant: A quantity first introduced by Einstein into his equations of general relativity to provide a kind of antigravity effect that would keep the Universe static; later discredited. Recently revived as a possible explanation for the 1998 discovery that the expansion of the Universe is accelerating.

Coulomb: The unit of electric charge.

CPU: See **central processing unit**.

Critical mass: The mass of fissile material (uranium, plutonium) needed for a self-sustaining nuclear chain reaction.

Curve of binding energy: A graph describing the energy release possible in forming atomic nuclei; shows that both fusion of light nuclei and fission of heavy nuclei can release energy.

Data bus: Channel for high-speed data transfer among different components of a computer.

Depletion region: The region surrounding a PN junction, in which there is a dearth of free charges.

Destructive interference: See **interference**.

Differential GPS: Use of two Global Positioning System receivers to reduce timing and atmospheric errors.

Diffraction: The phenomenon whereby waves change direction as they go around objects.

Diffraction limit: A fundamental limitation posed by the wave nature of light, whereby it is impossible to image an object whose size is smaller than the wavelength of the light being used to observe it.

Diffuse reflection: The reflection of waves, especially light, from a rough surface. The light is scattered at different angles and does not form an image.

Diffusion: The process where a material or type of particle moves from regions of higher concentration to regions of lower concentration.

Digital information storage: The encoding and storage of information as a sequence of digital 0s and 1s.

Diode: An electronic device using a PN junction to restrict the flow of electric current to one direction only.

Doped semiconductor: A semiconductor to which impurities have been added to alter the material’s electrical conductivity.

Doppler effect: The increase in perceived frequency (higher pitch for sound, bluer color for light) of waves when the source approaches the observer. Also, the decrease in frequency when the source recedes from the observer.

Drag: The backward-pointing aerodynamic force that resists the forward motion of an airplane, bird, or other heavier-than-air flying object.

Dynamic memory: Memory that stores information as electric charge. Must be refreshed several thousand times per second.

Elastic collision: A collision in which energy is conserved.

Electric charge: A fundamental property of matter that determines electric and magnetic interactions.

Electric current: A net flow of electric charge.

Electric field: The influence that surrounds an electric charge, resulting in forces on other charges.

Electric generator: A device that uses electromagnetic induction to convert mechanical energy to electrical energy. Typically, a generator involves a coil of wire rotating in a magnetic field.

Electromagnet: A magnet made by passing electric current through a coil of wire.

Electromagnetic induction: A fundamental phenomenon wherein a changing magnetic field produces an electric field.

Electromagnetic spectrum: The range of electromagnetic waves, organized by frequency or wavelength.

Electromagnetic wave: A structure consisting of electric and magnetic fields, each produced from the change in the other, that propagates through space carrying energy. Light is an electromagnetic wave. In vacuum, all electromagnetic waves travel at exactly the speed of light.

Electromagnetism: The branch of physics dealing with electricity and magnetism, described by Maxwell's equations as developed in the mid-19th century.

Electromechanical relay: A device using an electromagnetically actuated switch to allow one electric circuit to control another.

Electrostatic precipitator: A device that uses electric fields to remove particulate matter from smokestacks.

Energy: One of the two basic "things" that makes up the Universe. Energy is what makes everything happen.

Energy gap: The range of unavailable energies that separates two bands of allowed energy levels in a semiconductor.

Entropy: A measure of disorder. The second law of thermodynamics states that the entropy of a closed system can never decrease.

Equatorial orbit: An orbit that remains above Earth's equator.

Exclusive OR: The logical operation whose output is 1 if either, but not both, of its inputs is 1.

Extrinsic semiconductor: See **doped semiconductor**.

Faraday's law: The mathematical statement describing electromagnetic induction.

FET: See **field-effect transistor**.

Field-effect transistor (FET): A transistor in which an electric field exercises the control function.

First law of thermodynamics: The statement that energy is conserved, expanded to include thermal energy.

Flip-flop: An electronic circuit that has only two possible states. Used as the fundamental unit in static semiconductor memory.

Fluid friction: A friction-like force that slows the flow of a fluid, especially near a solid boundary.

Free fall: The state of motion of an object on which the only force acting is gravity. The object need not be moving downward!

Frequency: The number of complete wave cycles per unit of time; inverse of the wave period.

Friction: A force that acts between two surfaces, opposing any relative motion between them.

Fuel cell: A device that combines two chemicals (typically, hydrogen and oxygen), producing electric current in the process.

Fusion: A nuclear reaction in which light nuclei join to produce a heavier nucleus, releasing energy in the process.

Gate: The controlling electrode of a field-effect transistor; an unrelated definition is a circuit that performs a basic logic function.

General relativity: Einstein's 1915 theory that describes gravity as the curvature of spacetime.

Geosynchronous orbit: An equatorial orbit at an altitude of about 22,000 miles, where the orbital period is 24 hours. A satellite in such an orbit remains fixed over a point on the equator.

Gigabyte: A measure of computer memory, equal to about a billion bytes (exact value 2^{30} , or 1,073,741,824 bytes).

Gravitational lensing: The bending of light by the gravity of massive astrophysical objects.

Gravity: A universal attractive force that acts between all objects in the Universe.

Greenhouse effect: The trapping of outgoing infrared radiation by certain atmospheric gases, resulting in the warming of a planet.

Greenhouse gas: A gas that absorbs infrared radiation, thus contributing to the greenhouse effect.

Ground-fault interrupter: A safety device that senses imbalance in current on two wires, then shuts off the circuit to prevent electric shock.

Gyroscope: A rapidly spinning object whose rotation axis tends to maintain a fixed orientation.

Habitable zone: The region around a star where conditions are appropriate for life as we know it.

Half-life: The time it takes for half of the atoms in a sample of radioactive material to decay.

Heat capacity: A measure of the energy required to change an object's temperature.

Heat pump: A refrigerator run in reverse, pumping heat from the cooler outdoor environment into a building.

Hole: A place in a semiconductor where an electron is missing from the crystal structure. Acts as a positive charge.

Holographic image: A three-dimensional image made by recording interference patterns of wave fronts coming from the object being imaged.

Hyperfine transition: A transition between two very closely spaced atomic energy levels.

Induced electric field: An electric field produced not by electric charge but by a changing magnetic field.

Insulator: A material with no or few free electric charges and, thus, a poor carrier of electric current.

Integrated circuit: A circuit built on a single piece of silicon.

Interference: The process whereby two waves, occupying the same place at the same time, simply add to produce a composite disturbance. Interference may be constructive, in which the two waves reinforce to produce an enhanced composite wave, or destructive, in which case the composite wave is diminished.

Internal energy: The energy associated with random molecular motion; commonly but mistakenly called "heat."

Intrinsic semiconductor: A semiconductor made from a pure material.

Ion: An atom that has lost or gained an electron, thus possessing an electric charge.

Ionosphere: A region of Earth's atmosphere, beginning about 50 miles up, that contains free electrons and is, therefore, electrically conductive; affects the timing of GPS signals.

Kinetic energy: The energy associated with an object's motion.

Lagrangian point, L1: A point roughly 1 million miles sunward of Earth, where a spacecraft's orbital period is 1 year, allowing it to stay on the line between Earth and Sun.

Laser: A device that produces light or other electromagnetic radiation through stimulated emission; stands for *Light Amplification by Stimulated Emission of Radiation*.

Laser angioplasty: The use of laser beams to clear clogged arteries by vaporizing plaque.

Latent heat: Energy associated with a substance's being in a state requiring higher energy, as in the latent heat of water vapor, which can be released when the water condenses.

Law of inertia: The statement that a body in motion (or at rest) remains in uniform motion (or at rest) unless a force acts on it.

LCD: See **liquid-crystal display**.

LED: See **light-emitting diode**.

Lens: A piece of transparent material shaped so that refraction brings light rays to a focus.

Lift: See **aerodynamic lift**.

Light-emitting diode (LED): A diode engineered to produce visible or near-visible light when current flows across its PN junction.

Liquid-crystal display (LCD): A visual display device that uses electric fields to reorient the molecules of a liquid crystal, thereby altering the polarization of light.

Low-Earth orbit: An orbit whose altitude above Earth's surface is a small fraction of Earth's radius. The period of low-Earth orbits is about 90 minutes.

Magnetic field: The influence surrounding a moving electric charge (and, thus, a magnet) that results in forces on other moving charges (and on magnets or magnetic materials).

Magnetic resonance imaging (MRI): A procedure that uses spinning protons in a magnetic field to form images of the body's interior.

Magnetron: A special vacuum tube in which electrons undergo circular motion, producing microwaves.

Maxwell's equations: A set of four equations that describe all electromagnetic phenomena of classical physics.

Mechanics: The study of motion.

Megabyte: A measure of computer memory, equal to about a million bytes (exact value 2^{20} , or 1,048,576 bytes).

Memory: An electronic circuit that maintains a given state until the state is explicitly changed.

Metal-oxide-semiconductor field-effect transistor (MOSFET): A type of transistor widely used in computer circuits.

Microprocessor: The single-chip CPU of personal and other small computers.

Minority charge carriers: The free charges that are in a minority in a given semiconductor (electrons in P type, holes in N type).

Mirage: An image formed by refraction because of temperature gradients in the air.

Moderator: In a nuclear reactor, a substance that slows neutrons to make them more effective at causing fission.

Modern physics: The theories and descriptions of physical reality developed after about the year 1900, including specifically, relativity and quantum physics.

Momentum: A quantity that describes the "amount of motion" in a moving object, accounting for both velocity and mass.

Moore's law: The statement that the number of transistors per integrated circuit grows exponentially, doubling every year or two. Moore's law has held since the 1960s.

MOSFET: See **metal-oxide-semiconductor field-effect transistor**.

Motherboard: A circuit board holding the CPU, memory, and other components central to the operation of a computer.

MRI: See **magnetic resonance imaging**.

NAND: NOT AND; the logical operation whose output is the opposite of AND.

Natural greenhouse effect: The effect of natural greenhouse gases, particularly water vapor and carbon dioxide, in raising Earth's temperature some 60° F above what it would otherwise be.

Negative charge: The type of electric charge on the electron.

Net force: The sum of all forces acting on an object.

Neurons: Specialized cells that transmit electrochemical signals in the brain and nervous system.

Neutral buoyancy: The state of neither rising nor sinking that occurs for an object of the same density as the surrounding fluid.

Neutron: An electrically neutral component of the atomic nucleus.

Neutron activation: A process of inducing artificial radioactivity by bombarding substances with neutrons; the subsequent radioactive decay is used to identify the substances.

Newton's first law of motion: This is the same as the law of inertia.

Newton's second law of motion: The statement that an object's acceleration is proportional to the net force applied to it and inversely proportional to its mass.

Newton's third law of motion: The statement that forces always come in pairs; if one object exerts a force on a second object, the second exerts an equal but opposite force back on the first.

Nonthermal energy transfer: Energy transfer that does not rely on a temperature difference, as in a microwave oven.

Nonvolatile memory: Memory that retains information even when the power is off, as in a digital camera.

NOR: NOT OR; the logical operation whose output is the opposite of OR.

NOT: The logical operation whose output is the opposite of its input.

N-type semiconductor: A semiconductor doped so that the dominant free charges are negative electrons.

Nuclear chain reaction: An ongoing reaction in which neutrons released in nuclear fission go on to cause additional fission events.

Nuclear force: The force that binds protons and neutrons to form atomic nuclei.

Nuclear magnetic resonance (NMR): The process at the heart of MRI, whereby protons absorb radio waves of just the right frequency to set them precessing in a magnetic field.

Nuclear medicine: The use of radioactive substances to image body structures and analyze physiological processes.

Nucleosynthesis: The process of forming atomic nuclei, especially in stars and in the early Universe.

Ohm's law: The statement, valid for some materials, that the electric current is proportional to the applied voltage and inversely proportional to the material's resistance.

Optical storage medium: A medium, such as the CD or DVD, that encodes information in ways that can be read using light.

Optics: The branch of physics dealing with light and its behavior.

OR: The logical operation whose output is 1 if either or both inputs are 1.

Pacemaker: A specialized group of cells that provides the signal to govern the rhythmic beating of the heart.

Parallel communications: Data transfer that moves many bits simultaneously on separate wires.

Period: The time interval between two successive wave crests; equivalently, the time for a complete wave cycle.

PET: See **positron emission tomography**.

Phase change: A change in a material, as from solid to liquid or liquid to gas, that occurs abruptly at certain values of temperature and pressure.

Phase diagram: A diagram showing how the phases of a substance relate to its temperature and pressure.

Photolithography: A process using light to lay down patterns for forming integrated circuits.

Photovoltaic cell: A semiconductor device that converts light directly into electrical energy.

Piezoelectric device: A device using a material that generates electricity when squeezed or distorted; conversely, the device changes size or shape when a voltage is applied to it.

Pixel: An individual element of a digital image.

Plasma: An ionized gas, sometimes called the "fourth state of matter."

PN junction: A junction of P- and N-type semiconductors, with the property that electric current can flow in only one direction.

Polar orbit: An orbit that passes over Earth's poles. As Earth rotates, a satellite in polar orbit passes over every point on the planet.

Polarization: The direction of an electromagnetic wave's electric field.

Population inversion: A situation in which more higher level atomic states are populated than are lower level states. Needed for laser action.

Positive charge: The type of electric charge on the proton.

Positron emission tomography (PET): A medical imaging technique using gamma rays from the annihilation of positrons (anti-electrons) released in the decay of radioactive substances.

Potential energy: Stored energy associated with a configuration of objects.

Power: The rate of producing or expending energy. In electrical devices, power is the product of voltage and current.

Precession: The gradual change in direction of a rotating object's rotation axis as a result of an applied torque.

Proton: A positively charged component of the atomic nucleus.

P-type semiconductor: A semiconductor doped so that the dominant free charges are positive holes.

Pulsar: A rapidly spinning neutron star.

Quantum computing: Computing based on the states of quantum-mechanical systems.

Quantum physics: The theory, developed in the early 20th century, that describes physical reality at the atomic scale and below. In this realm, the discrete, "quantized" nature of both matter and energy become important.

Radiation: Heat transfer by electromagnetic waves.

RAM: See **random-access memory**.

Random-access memory (RAM): Memory whose individual storage locations can all be accessed in equal time, as opposed to sequential memory, such as that on magnetic tape.

Read-only memory (ROM): Memory whose state cannot be changed.

Rechargeable battery: A battery in which the passage of electric current from an outside source results in the storage of chemical energy.

Reflection: The phenomenon whereby a wave strikes a material and rebounds at the same angle with which it struck the material.

Refraction: The phenomenon of waves changing direction of propagation when going from one medium to another.

Resistance: The property of a material that describes how it impedes the flow of electric current.

Resistor: A device formulated to have a specific electrical resistance.

Reverse bias: The condition in which a voltage is applied across a PN junction, with positive to the N-type side. Results in very little electric current.

ROM: See **read-only memory**.

Rotational inertia: A measure of an object's resistance to change in rotational motion.

Second law of thermodynamics: A general principle stating that systems tend to evolve from more ordered to less ordered states.

Semiconductor: A material that lies between insulators and conductors in its capacity to carry electric current. The electrical properties of semiconductors are readily manipulated to make the myriad devices at the heart of modern electronics.

Semiconductor memory: Memory made with transistors and other devices. The fastest memory used in computers.

Serial communications: Data transfer that moves one bit at a time, using a single wire.

Shock wave: A very strong, abrupt wave produced when a wave source moves through a medium at a speed faster than the waves in that medium. An example is a sonic boom from a supersonic airplane.

Sliding friction: The frictional force between two surfaces in relative motion; smaller than static friction.

Special relativity: Einstein's 1905 theory that shows how all uniformly moving frames of reference are equivalent as far as the laws of physics are concerned. Requires modification of our commonsense notions of time and space.

Specular reflection: Reflection off a smooth surface that appears shiny and produces an image, as in a mirror.

Spontaneous emission: The emission of light or other electromagnetic energy as an electron jumps spontaneously from a higher energy level to a lower one.

Standing waves: Waves that “stand” without propagating on a medium of fixed size. The vibrations of a violin string are standing waves.

Static electricity: Electricity associated with stationary distributions of electric charge.

Static friction: The frictional force between two surfaces at rest relative to each other.

Static memory (SRAM): Semiconductor memory in which information is stored in the states of flip-flops.

Steady-state theory: The idea, now widely discredited, that the overall structure of the Universe never changes.

Stimulated emission: The emission of light or other electromagnetic energy as an electron jumps from a higher energy level to a lower one, stimulated to do so by the nearby passage of similar electromagnetic energy.

Sublime: To change directly from solid to vapor, without going through the liquid state.

Superconductor: A material that, at sufficiently low temperature, exhibits zero resistance to the flow of electric current.

Superheated: A liquid above its boiling point but nevertheless not boiling.

Supernova: The violent explosion marking the endpoint of massive stars.

Temperature: A measure of the average thermal energy.

Terminal speed: The maximum speed reached by a falling object, which occurs when air resistance becomes equal in magnitude to the force of gravity.

Theory of Everything: An as-yet-undeveloped theory that would describe all of physical reality.

Thermal energy: See **internal energy**.

Thermal energy balance: A state wherein energy leaving a system is balanced by incoming energy.

Thermal pollution: Waste heat dumped to the environment, usually associated with the thermodynamic inefficiency of power plants.

Thermistor: A temperature-measuring device utilizing the property that the resistance of an intrinsic semiconductor decreases with increasing temperature.

Thermocouple: A device that uses the thermoelectric effect to measure temperature.

Thermodynamics: The branch of physics dealing with heat and related phenomena.

Thermoelectric effect: The production of a voltage at a junction of two dissimilar materials when heated.

Toner: The small particles that take the place of ink in dry copying and laser printing (xerography).

Torque: The rotational analog of force; torque depends on force and where that force is applied.

Total internal reflection: Complete reflection that occurs as light attempts to go from a more dense to a less dense medium, as from water to air.

Transformer: A device that uses electromagnetic induction to transform high-voltage/low-current electricity to low-voltage/high-current and vice versa.

Transistor: A semiconductor device with three separate electrical connections, in which current or voltage in one circuit controls current or voltage in another circuit. The basic control element in both digital and analog electronics.

Truth table: A table that displays all possible states of a logic gate.

Volatile memory: Memory that stores information only as long as power is applied.

Voltage: A measure of the energy per unit of electric charge.

Watt: A unit of power, equal to 1 joule of energy per second.

Wave: A traveling disturbance that carries energy but not matter.

Wavelength: The distance between two successive wave crests.

Weight: The force that gravity exerts on an object.

Word: A sequence of binary bits, usually 32 or 64 bits, on which a computer performs operations.

Working fluid: A substance used in refrigerators and engines to transfer heat; often undergoes phase changes in the process.

XOR: See **exclusive OR**.

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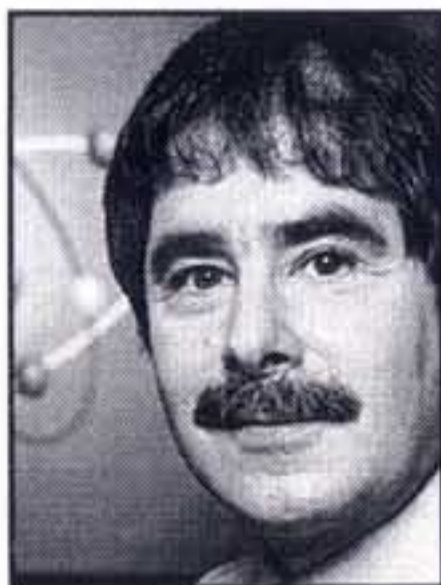
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THE GREAT COURSESSM

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Physics in Your Life

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Part 3

Course Guidebook

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Richard Wolfson is Benjamin F. Wissler Professor of Physics at Middlebury College, where he has also held the George Adams Ellis Chair in the Liberal Arts. He did undergraduate work at MIT and Swarthmore College, graduating from Swarthmore with a double major in physics and philosophy. He holds a master's degree in environmental studies from the University of Michigan and a Ph.D. in physics from Dartmouth. Professor Wolfson's published work encompasses such diverse fields as medical physics, plasma physics, solar energy engineering, electronic circuit design, observational astronomy, theoretical astrophysics, nuclear issues, and climate change. His current research involves the sometimes violently eruptive behavior of the Sun's outer atmosphere, or corona. He also continues an interest in environmental science, especially global climate change.

Dr. Wolfson is particularly concerned with making science relevant to nonscientists and to students from all walks of academic life. His textbook, *Physics for Scientists and Engineers* (Addison Wesley, 1999), is now in its third edition and has been translated into several languages. His books *Nuclear Choices: A Citizen's Guide to Nuclear Technology* (MIT Press, 1993) and *Simply Einstein: Relativity Demystified* (W.W. Norton, 2003) exemplify Wolfson's interest in making science accessible to nonscientists. He has also published in *Scientific American* and has produced videotaped courses for The Teaching Company, including *Einstein's Relativity and the Quantum Revolution: Modern Physics for Nonscientists*, *Energy and Climate: Science for Citizens in the Age of Global Warming*, and *Physics in Your Life*. Professor Wolfson has spent sabbaticals at the National Center for Atmospheric Research in Boulder, Colorado; at St. Andrews University in Scotland; and at Stanford University.

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Physics in Your Life

Scope:

Physics is the science that governs the workings of physical reality at its most fundamental level. Thus, physics is important in understanding the ultimate nature of the Universe. But it is equally important in our everyday lives. The commonest actions—such as walking, breathing, or driving a car—are all based on principles of physics. The natural world delights us with a host of physics-based phenomena, from rainbows and snowflakes to the blue of the sky, the daily rotation of our planet, and the celestial companionship of the orbiting Moon. And physics-based technology is ubiquitous in modern life—from the CDs and DVDs that entertain and inform us to the antilock brakes that make driving safer, the global positioning system that helps us navigate about our planet, medical imaging that enhances our health, microwaves that cook our food, airplanes that transport us swiftly about the globe, lasers that scan our supermarket purchases, and the semiconductor electronics at the heart of our computers, cell phones, digital cameras, personal digital assistants, and audiovisual systems.

This course introduces principles of physics through their application to everyday life. It's more than a course in physics and more than a laundry list of "how things work." Rather, it combines the two, offering a back-and-forth interplay between everyday applications of physics and the physics principles needed to understand them. Applications include the simplest everyday activities, natural phenomena that affect our everyday lives, and especially, modern technology. Physics principles covered range from Newton's laws of motion, known for hundreds of years but still vitally relevant, to concepts from atomic and quantum physics that underlie such diverse technologies as semiconductor electronics, lasers, and medical imaging.

The course is organized into six modules of six lectures each. The first five modules deal with specific realms of physics and related applications; the sixth is a potpourri of physics applications that draw from more than one of the earlier modules. Although there's no obviously straightforward path through the myriad applications included here, the lectures are designed to build on each other and to flow smoothly from one to the other. *Physics in Your Life* is aimed at intelligent nonscientists, and the presentation of physics concepts and applications is entirely nonmathematical.

Given that the course is presented on audiovisual media, the first module—**"Sight and Sound"**—begins with the technology behind CDs and DVDs, not only explaining how these work but raising questions that lead to the basic principles of light and sound. Subsequent lectures explore these principles in application to such diverse topics as rainbows, optical fibers for communications, musical instruments, and laser vision correction.

“**Going Places**” looks at motion and its applications, from simple walking to modern automobile technology, airplane flight, and space travel. This module is based on Newton’s laws, generalized to include such diverse topics as fluid motion, conservation of energy, and the dynamics of space flight from communications satellites to interplanetary exploration.

“**Plug In, Turn On**” explores the electromagnetic basis of so many contemporary technologies and natural phenomena. Matter itself sticks together through electrical interactions, while the intimate relations between electricity and magnetism are at the heart of technologies ranging from electric motors and generators to videotapes and credit cards. We’ve learned numerous ways to produce electrical energy, and we respect not only the good it can do but also the dangers it poses. Finally, electricity and magnetism join to make possible the electromagnetic waves that include visible light and that enable the growing host of wireless technologies in our everyday lives.

“**From Atom to Computer**” starts with basic ideas in atomic physics and builds through explanation of the semiconductor materials at the basis of today’s electronics; the operation of the transistors that are the essential electronic components; the agglomeration of close to a billion transistors in today’s most sophisticated integrated circuits; the simple logical operations that underlie all our computers can do; and the structural organization of an entire computer.

The fifth module, “**Fire and Ice,**” introduces concepts and applications related to heat. Lectures range from “Physics in the Kitchen” to “Life in the Greenhouse,” the latter a look at how principles of thermal physics establish Earth’s climate and how we humans may be changing that climate. “The Tip of the Iceberg” describes the thermal response of materials, including the unusual behavior of water in both liquid and solid form—a behavior with enormous implications for life on Earth. The module ends with a look at humanity’s appetite for energy in the face of limitations posed by the laws of thermodynamics. Those laws themselves are the subject of “Like a Work of Shakespeare,” a lecture so titled because one such law has been deemed as essential to an educated person as the Bard’s writings.

The sixth module is a potpourri of applications and principles from the specific to the cosmic. “Your Place on Earth” describes the workings and increasingly pervasive applications of the space-based Global Positioning System (GPS). “Dance and Spin” looks at applications of rotational motion from dance to pulsars. “The Light Fantastic” explores the operation of lasers and their applications in everything from supermarket scanners to the Internet. “Nuclear Matters” looks at the behind-the-scenes roles that nuclear physics plays in our lives. “Physics in Your Body” emphasizes modern medical techniques, such as MRI and particle-beam treatments for cancer. The course ends with “Your Place in the Universe,” tracing the history of your own body from the earliest events of the Big Bang.

Module Five: Fire and Ice

Lecture Twenty-Five

Keeping Warm

Scope: Phenomena involving heat play a major role in our lives. We humans can survive only in a narrow temperature range. The Sun’s energy keeps Earth’s temperature near that range, while technology provides further control over our indoor thermal environment. Technically speaking, *heat* refers to energy that’s moving from one place to another as a result of a temperature difference. Both natural and technological systems exploit a variety of mechanisms to facilitate such heat transfer. Understanding heat transfer lets us design more efficient buildings, make instantaneous measurements of body temperature, diagnose disease, and cook delicious food. On a larger scale, the same principles let us take the temperature of the stars and of the Universe itself. And understanding heat transfer helps us recognize the changes we humans are causing in Earth’s climate.

Outline

- I. *Heat*, loosely, refers to the energy associated with random motions of the atoms and molecules that make up matter. Strictly speaking, that energy should be called *internal energy* or *thermal energy*. *Temperature* is essentially a measure of thermal energy on a per-molecule basis. The term *heat* describes a flow of energy resulting from a temperature difference.
 - A. Common temperature scales, including degrees Fahrenheit and degrees Celsius, are based on everyday occurrences, such as the freezing and boiling of water. However, because temperature is a measure of energy, there’s an absolute minimum temperature, corresponding to the lowest possible energy of a system. This *absolute zero* lies about 460 degrees below 0 Fahrenheit and 273 degrees below 0 Celsius.
 - B. Temperature alone tells nothing about how much thermal energy an object contains. We’re usually less interested in total energy in an object than in the energy associated with a change in its temperature. The energy involved per degree of an object’s temperature change is the object’s *heat capacity*.
 1. For equal amounts of material, different substances have different heat capacities.
 2. Water has a particularly high heat capacity. That’s why it takes so long to bring water to a boil on the stove, and it’s also why large lakes have a moderating effect on the surrounding climate.
- II. When an object’s temperature differs from its surroundings, energy flows

from the object to the surroundings (if the object is hotter) or from the surroundings to the object (if it's cooler). Because this energy is flowing as a result of a temperature difference, it's properly called *heat*. There are three common mechanisms for such heat transfer:

A. Conduction occurs when two objects or substances are in direct contact. Particles in the hotter substance are moving faster, and when they collide with the slower moving molecules in the cooler substance, they transfer energy. Because the rate of heat transfer is proportional to the temperature difference, a greater temperature difference makes for a greater heat flow. That's why it takes more energy to heat your house in colder weather.

1. Materials differ in their conduction effectiveness. Metals are very good conductors of heat, while water is moderately good and air is a poor conductor. Such materials as Styrofoam and fiberglass insulation, which contain trapped air with very little solid material, are designed to be especially poor heat conductors and, thus, to inhibit heat flow.
2. The thermal conductivity of building materials is what ultimately determines how much energy we must supply to heat or cool our houses. The familiar R-value used to rate insulation is a measure of insulation effectiveness. R-19 fiberglass insulation, for example, loses 1/19 of a British thermal unit of energy for each square foot of area, for each degree Fahrenheit temperature difference from one side of the insulation to the other. (One Btu is the energy needed to raise a pound of water 1 degree Fahrenheit; it's a unit used almost solely in the United States and is analogous to the calorie, which is the energy needed to raise 1 gram of water 1 degree Celsius.) Because R-values add, it's easy to figure out the heat loss through a composite structure, such as a wall.
3. I'm often asked whether it makes sense to turn one's heat down at night, because of the need for extra heat to warm the house in the morning. Pause a minute and think about this, given what you know about heat transfer by conduction. In fact, you're always better off turning down the heat, because a lower temperature means a lower rate of heat transfer.

B. Convection is the transfer of energy by the motion of a fluid, such as air or water. Because warmer fluid is less dense, it rises. As it does so, it gives up heat to its cooler surroundings. The now-cooled air eventually sinks, resulting in a continuous circulation of fluid that transfers heat from a warmer, lower level to a higher, cooler level.

1. Convection is responsible for several everyday heat-transfer occurrences. When you heat water on the stove, heat flows from the stove into the water by conduction. Heating at the bottom of the water then sets up convection currents that transfer heat throughout

the water. On a larger scale, heat sources in a house set up gentle convection currents that circulate warm air throughout the house.

2. Convection is also important in natural systems. Giant convection cells associated with strong heating in Earth's tropics help transfer energy poleward, making the planet a more uniformly warm place than it would otherwise be. Coupled with Earth's rotation, these convective flows also result in the prevailing west-to-east winds in Earth's mid-latitudes. Convection just below the visible surface of the Sun transports the enormous energy generated in the Sun's interior outward to the surface. And Earth's continents drift about slowly on convection currents resulting from rising heat in Earth's mantle. Finally, convection in the electrically conducting fluids in the interiors of Sun and Earth are responsible for these bodies' magnetic fields.
3. It's because of convection that an air space alone is not very effective at preventing heat loss in buildings. Properly designed insulation, such as fiberglass, Styrofoam, or goose down, traps air and keeps it from moving, thus exploiting air's poor thermal conduction while preventing energy loss by convection.

C. Radiation is the transfer of energy by electromagnetic waves. At temperatures above absolute zero, all objects emit electromagnetic waves, because the thermal motion of their constituent particles involves the acceleration of electric charge (Lecture Eighteen). When an object is warmer than its surroundings, radiation results in a net loss of energy. Radiation increases dramatically with increasing temperature (as *temperature*⁴), so it's particularly important at high temperatures. A hot stove burner and the filament of a lightbulb are both losing energy almost entirely by radiation; so is the Sun itself and, for that matter, so is the Earth. When an object—such as a planet or star—is surrounded by vacuum, then radiation is the only means of heat transfer available.

1. Shiny objects reflect radiation, which is why building insulation is often covered with aluminum foil. That's also why vacuum ("thermos") bottles are shiny on the inside; the vacuum prevents heat flow by conduction or convection, and the shiny coating turns back radiation. This is also why high-quality windows have so-called low-E coatings that inhibit energy loss by radiation.
2. Not only does the amount of radiation increase with temperature, but so does the frequency of the waves emitted—and frequency is related to color. Thus, it's the temperature that ultimately determines the color of a hot, glowing object. The Sun, at nearly 6000 °C, glows with visible light, essentially white. A lightbulb filament is at about 3000 °C, and it glows with a yellower light. Turn down the current to the filament, and it gets redder. Even when an object is too cool for its glow to be visible, it still

radiates—now in the infrared or even radio region of the electromagnetic spectrum.

III. With no additional energy, a hot object will gradually lose energy by heat transfer to its surroundings, eventually reaching the same temperature as the surroundings.

A. To keep an object warmer than its surroundings requires a supply of energy. If the energy supplied to the object exactly balances the energy lost by conduction, convection, and/or radiation, then the object's temperature will remain constant. This is the state of *thermal energy balance*.

1. In buildings and other engineered systems, a temperature-sensitive switch called a *thermostat* is used to turn the energy source on if the temperature drops below a set point and off when it rises much above that point. The direct effect is to maintain the desired temperature; consequently, the energy supplied to the building is automatically made equal to the energy lost.

2. In warm-blooded mammals, including humans, the brain's hypothalamus monitors changes in body temperature and orders a variety of compensating mechanisms to maintain a constant temperature. These include changes in metabolic rate, changes in the configuration of hair or fur, sweating, and constriction or dilation of blood vessels. The result in all cases is to maintain internal energy generation at a rate that balances energy loss to the environment.

B. Even without active regulation mechanisms, an object with a fixed energy supply will automatically reach a state of energy balance. That's because all three heat-transfer mechanisms increase the rate of heat flow as the temperature difference increases.

1. Consider, for example, a solar-heated greenhouse with no other energy source. If it's at the same temperature as its surroundings, then there's no heat loss. However, because there's energy coming in from the Sun, the greenhouse temperature goes up. But then heat begins to flow out. As long as the rate of outflow is less than the rate of solar energy coming in, the greenhouse will continue to warm. As its temperature increases, however, so does the heat loss. Eventually, a temperature is reached at which the heat loss exactly balances the solar input. That's the energy-balance temperature, and as long as the solar input stays constant, the greenhouse will maintain that temperature. If the solar input drops, the greenhouse will lose heat at a greater rate than it gains solar energy, so it will cool down. But then the heat-loss rate drops, and eventually, a new balance is established.

2. This phenomenon of energy balance is what determines temperatures in a wide variety of technological and natural

systems. Why is the filament of a lightbulb at about $3000\text{ }^{\circ}\text{C}$? Because at that temperature, the rate of energy loss by radiation is equal to the rate at which electrical energy is supplied to the filament. If it were cooler, the energy loss would be lower and the electrical energy input would exceed the loss; the filament would heat up. If it were hotter, the loss would exceed the electrical input, and it would cool down. Thus, a state of energy balance is automatic. Why is the Sun at $6000\text{ }^{\circ}\text{C}$? Because at that temperature, the rate at which it loses energy by radiating sunlight balances the nuclear energy generation in the Sun's core.

3. Energy balance is the ultimate determinant of Earth's climate. We'll take a closer look in the next lecture.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 16.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 6.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction*, chapter 10.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 19.

Questions to Consider:

1. The temperature of a candle flame is about $2500\text{ }^{\circ}\text{F}$. A bathtub full of water might be at $100\text{ }^{\circ}\text{F}$. Which has more "heat" or, to be precise, more thermal energy?
2. What will doubling the R-value of all the walls and windows in your house do to your heating bill?

Lecture Twenty-Six

Life in the Greenhouse

Scope: Earth's climate is established by the same energy-balance condition that governs a building, a star, or a lightbulb. Earth receives energy from the Sun, mostly in the form of visible light. Our planet returns energy to outer space, mostly in the form of longer wavelength infrared radiation (IR). For a stable climate, energy input and output must be in balance. The details of that balance are determined by a number of factors, especially the composition of the atmosphere as it affects outgoing infrared radiation. Although the atmosphere is largely transparent to the visible radiation from the Sun, it is much more opaque to the outgoing infrared. Thus, the atmosphere acts like an insulating blanket, and as a result, Earth is warmer than it otherwise would be. This so-called *greenhouse effect* is perfectly natural and has been a feature of planet Earth—and our neighbor planets—for eons. But we humans are altering the composition of the atmosphere, leading to an enhanced greenhouse effect and a warming planet.

Outline

- I. Solar energy provides 99.98 percent of the energy input to Earth and its atmosphere. (Nearly all the rest is from within Earth's interior, and a tiny amount of energy comes, via tides, from the orbital motion of the Moon.) For Earth's climate to be stable, the solar energy input must be balanced by energy Earth returns to outer space.
 - A. Because Earth is relatively cool, it loses energy by radiating invisible infrared radiation (recall the lightbulb demonstration from the previous lecture)—as opposed to the visible radiation from the hot Sun.
 1. Knowing the law that describes energy loss by radiation, it's a simple matter to equate the incoming solar energy with the radiation loss and solve for the temperature. The result is a calculated average temperature for Earth of about 0 °F or -20 °C—certainly in the right ballpark but seeming rather cold for a global average.
 2. In fact, Earth's global average temperature is about 60 °F or 15 °C. Something else must be affecting Earth's energy balance.
 - B. That something is Earth's atmosphere.
 1. Because the atmosphere is transparent to the visible light from the Sun, most of the incident sunlight reaches Earth's surface. Some is reflected off clouds, and a little is absorbed in the atmosphere.
 2. The atmosphere is substantially opaque to the outgoing infrared radiation from Earth's surface. Specific gases that absorb infrared

radiation are responsible for making the atmosphere opaque. Most important among these are water vapor and carbon dioxide.

3. These infrared-absorbing gases are called *greenhouse gases*, because they function something like the glass cover of a greenhouse, trapping heat within. Actually, the term *greenhouse gas* is somewhat of a misnomer, because the primary function of the glass in a greenhouse is to keep warm air from escaping—thus inhibiting convective heat loss, rather than radiation.
 4. The greenhouse gases act as an insulating blanket. In a house, insulation reduces the amount of energy we need to consume to maintain a desired temperature. But on a planet, the energy input is fixed by the Sun and the planet's distance from it. Earth still must get rid of the same amount of energy—as if you kept the furnace on the same amount of time even after adding insulation to your walls. To get that energy out through the “insulation” of the greenhouse gases, Earth's surface must be warmer than it otherwise would be. That's the *greenhouse effect*.
 5. The *natural greenhouse effect*, caused primarily by water vapor and, to a lesser extent, by carbon dioxide, keeps Earth on average about 60 °F or 33 °C warmer than it otherwise would be. Our planet is a lot more comfortable because of the greenhouse effect!
- II. How do we know this greenhouse explanation for Earth's climate is correct? The answer lies in a tale of three planets:
 - A. We can't do controlled experiments on the Earth (although it's arguable that we're engaged in an uncontrolled experiment as we alter the composition of the atmosphere), but we do have two neighbor planets, each with a very different atmosphere, and we can apply the theory to them. Because we know each planet's distance from the Sun, we can determine how much energy it receives. We know that a stable climate requires that each planet lose through infrared radiation as much energy as it gains from the Sun.
 1. Mars's atmosphere is very diffuse, with less than 1 percent the density of Earth's atmosphere. Consequently, we don't expect much of a greenhouse effect on Mars. Indeed, Mars's average temperature is only a few degrees warmer than a simple energy-balance calculation would suggest.
 2. A simple calculation suggests an average temperature for Venus of around 50 °C or 122 °F—a bit warmer than Earth because Venus is closer to the Sun. In fact, Venus's average surface temperature is nearly 500 °C, or about 900 °F. The huge discrepancy arises because Venus has an atmosphere 100 times denser than Earth's, and it's 95 percent carbon dioxide. Venus has a runaway greenhouse effect that long ago raised the temperature far above what it would otherwise be.

B. These three planets—Venus, Earth, Mars—each in a different way helps confirm the theory of the greenhouse effect.

III. Since the beginning of the industrial era, human activities—mainly the burning of fossil fuels—have increased atmospheric carbon dioxide by about 30 percent.

A. Of the solar energy captured by plants in the process of photosynthesis, a tiny fraction is not cycled through the Earth-atmosphere system but ends up buried in the ground as the fossil fuels coal, oil, and natural gas. The fossil fuels store not only energy but also carbon. It has taken tens of millions of years to accumulate today's reserves of fossil fuels.

B. We're burning fossil fuels at a far greater rate than they're being stored, thus upsetting the balance of the carbon cycle and increasing atmospheric carbon dioxide.

C. Climate data going back hundreds of thousands of years show a clear link between temperature and atmospheric carbon dioxide.

1. Carbon dioxide and temperature have fluctuated together, with much of the time spent in low-temperature, low-CO₂ states called *ice ages*.

2. Every hundred thousand years or so, a briefer (about 10,000-year) warm period occurs. We're in such a warm period now. These fluctuations are believed caused by subtle changes in Earth's orbit, enhanced by feedback effects in the climate system. The average temperature difference between a warm period and an ice age is only about 10 °F.

D. The graph of ancient climate shown on the video gives a maximum of 280 parts per million for Earth's atmospheric CO₂ concentration before the industrial era. Where would today's level be on this graph?

1. Today's atmospheric carbon dioxide is higher than anything the planet has seen in the past half-million years and probably in the past 20 million years.

2. Although this glosses over many subtleties and complexities, that's the main reason for concern that we humans are making substantial changes in Earth's climate.

E. Our best estimates from computer climate models suggest that Earth will warm some 1.5–6 °C (3–9 °F) by the year 2100. That compares with a warming of about 0.6 °C (1 °F) during the 20th century and 6 °C (10 °F)—but in the other direction—between now and the last ice age. Even a few degrees' change is sure to have a significant impact on agriculture, sea level, weather patterns, and ecosystems. Whether or not the physics of Earth's energy balance is important in your life, it will be in your children's and grandchildren's!

Suggested Reading:

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction*, chapter 10, pp. 202–203.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 19, pp. 488–489.

Stephen H. Schneider, Armin Rosencranz, and John O. Niles, eds., *Climate Change Policy: A Survey*, chapter 1.

Questions to Consider:

1. Is the greenhouse effect good for the Earth or not? Discuss.
2. A temperature change of a few degrees doesn't seem like much; after all, temperature can vary by tens of degrees in a single day. Why, in the context of past climate change, might a few degrees be significant?

Lecture Twenty-Seven

The Tip of the Iceberg

Scope: Things don't just heat up or cool down in response to heat flows. They also expand and contract. More dramatically, they change state—melting and boiling to form liquids and gases or condensing and freezing. A substantial amount of energy is involved in these transformations, and which transitions occur may depend on external conditions, such as atmospheric pressure. One of the most commonplace of substances—water—is unusual in its thermal behavior. Unlike most substances, water expands when it freezes, and consequently, ice floats. This abnormal behavior also affects liquid water near the freezing point, with profound consequences for living things.

Outline

- I. Heat flow into or out of an object does more than gradually raise or lower the object's temperature. It also changes an object's dimensions and, more dramatically, may cause a change of state.
- II. Most substances expand when heated. This is the result of the increasing energy of individual molecules, which interact more violently when heated and, therefore, maintain a slightly larger spacing.
 - A. For typical solids, thermal expansion is a fairly small effect, amounting to only about one 1/1000 of a percent change in length for each degree change in temperature.
 1. Engineered structures need to account for thermal expansion or disaster can result. Bridges, parking garages, and similar structures are equipped with expansion joints to allow for thermal expansion without cracking the structure.
 2. Precision instruments, such as telescopes and other optical systems, are often built from special materials designed to minimize thermal expansion. Otherwise, even small changes in temperature could compromise performance.
 3. Bonding together two materials with different expansion rates gives a structure that bends as its temperature changes. This effect is widely used in such applications as thermostats and automatic greenhouse vents.
 - B. Liquids generally show more thermal expansion than solids, and gases, even more.
 1. Thermal expansion in a column of liquid makes for a simple, accurate thermometer.

2. Thermal expansion in closed systems can be dangerous. If you have a water-based home heating system, it better be equipped with an expansion tank to accommodate the extra volume as the water heats up. Your water heater has safety relief valves that discharge water if pressure builds up from thermal expansion, thereby preventing a possible explosive failure of the water heater. Your car's cooling and fuel systems also have devices to handle thermal expansion of coolant and fuel.
 3. One projected consequence of global warming (discussed in the previous lecture) is a rise in sea level. Roughly half of that rise will be from thermal expansion of the ocean waters (the rest is from melting ice).
- C. Although at most temperatures water expands when heated, very near its freezing point this most common of substances is unusual. Between 0 and 4 °C (32 and about 39 °F), water's volume actually decreases as it warms. Thus, water is at its densest at 4 °C (about 39 °F).
1. This unusual behavior means that water at 4 °C sinks to the bottom of lakes, and in many deep lakes, the bottom temperature remains at this level year round. In the summer, temperature rises toward the surface, but in the winter, it drops. Either way, the lake is stable, with less dense water on top of denser water.
 2. However, twice a year, in spring and fall, the lake surface warms or cools through 4 °C. At that point, denser water overlies less dense water, and the lake "overturns," in the process churning up nutrients from the bottom and generally revitalizing the lake.
- III. A more dramatic thermal effect involves changes of state of a substance—from solid to liquid, liquid to gas, or even solid to gas—that occur abruptly at particular temperatures.
- A. A substantial amount of energy must be added or removed to effect a change of state (also called a *phase change*). For example, it takes nearly as much energy to melt a chunk of ice as it does to raise the resulting water from the freezing to the boiling point. And it takes more than five times as much energy to boil the water away, turning it all into a gas.
 - B. While a substance is changing state, its temperature doesn't change. Once ice is brought to its melting point (0 °C or 32 °F) and begins to melt, the ice/water mixture stays at that temperature until the ice is all melted. Only then can the temperature begin to rise again. On cooling, water reaching the freezing point (again 0 °C or 32 °F) stays at that temperature until it's all frozen.
 - C. Although it need not be any warmer than ice, liquid water contains more energy—the energy that was added to melt the ice. Similarly, water vapor contains a lot more energy than liquid water, even if they're

both at the boiling point (100 °C or 212 °F). When water freezes to ice or water vapor condenses to liquid water, that energy is released.

1. This energy “stored” in the “higher” state is sometimes called *latent heat*, because it can be released by changing a substance to the “lower” state.
2. Even the slow process of evaporation that occurs below the boiling point requires energy. (The boiling point is special because here, the pressure of the evaporated vapor is equal to atmospheric pressure.) Evaporation is, therefore, a cooling process—a fact that underlies the operation of your household refrigerator (more on this in the next lecture).
3. Latent heat plays a major role in weather and climate. As solar energy evaporates ocean water, the air becomes both warmer and moister. This warm, moist air rises, taking with it the energy that went into transforming liquid water into vapor. Higher in the atmosphere, it may re-condense to form clouds—in the process, releasing its energy. The energy released from latent heat is what powers tropical hurricanes and explains why they quickly lose strength when they move over land.

D. The temperature at which state changes occur depends on pressure. That’s why water boils at lower temperatures at high altitudes, and it’s why pressure cookers and nuclear power plants can heat water to higher than 212 °F without it boiling.

1. A *phase diagram* summarizes the relation between solid, liquid, and gaseous phases at different temperatures and pressures. At a fixed pressure, such as Earth’s atmosphere provides, many substances show all three phases. But at other pressures or for other substances at normal atmospheric pressure, there may be only two phases. That’s the case for carbon dioxide, which *sublimes*, changing directly from solid “dry ice” to gas.
2. The phase diagram shows two other interesting features that, for most substances, fall outside the realm of “everyday physics.” Above the *critical point*, liquid and gas become indistinguishable, with the substance making a gradual transition from dense liquid to diffuse gas as the temperature increases (for water, this occurs at 374 °C and a pressure more than 200 times atmospheric). Fluids near the critical point exhibit some remarkable properties, many of which are best seen in the apparent weightlessness of an orbiting spacecraft. And there’s a special point, the *triple point*, where solid, liquid, and gas can all coexist. That point occurs at a unique temperature, and thus, it provides a rock-solid way to calibrate temperature scales.

E. Once again, water is unusual. Unlike most other substances, its solid phase is less dense than the liquid; therefore, ice floats. This has

profound implications for aquatic organisms; if ice were denser than water, lakes would freeze from the bottom up and aquatic life would be difficult. Instead, ice forms an insulating layer on the surface, allowing life to continue beneath. Our planet would be a very different place if water behaved like most substances.

1. The reason for water’s unusual properties lies in the crystal structure of ice. Individual water molecules (H_2O) bond hydrogen to oxygen to make a very open structure with a lot of empty space—hence the low density. Incidentally, this is why snowflakes are six-sided.
2. This unusual structure means that ice can be made to melt under pressure. This helps you pack loose snow into a snowball.
3. A residue of this bonding effect keeps the molecules in very cold liquid water farther apart than they otherwise would be—hence water’s unusual property of expanding when cooled at temperatures below 4 °C.
4. Because ice is only about 10 percent less dense than water, it floats low in the water (recall Lecture Ten)—which is why all we see is the “tip of the iceberg.”

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 17.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction*, chapter 10.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 20.

Questions to Consider:

1. When you emerge from swimming, you feel quite cool until you get dry—even on a hot day. Why?
2. You add some ice to a glass of water and wait a while. When you come back, there’s still ice in the water. Is the water warmer than the ice? Discuss.

Lecture Twenty-Eight

Physics in the Kitchen

Scope: We cook food to enhance its flavor and texture and to kill harmful bacteria. Before cooking, we store many foods under refrigeration. Refrigeration inhibits bacterial growth and slows natural chemical changes. Cooking is the opposite, intentionally changing the physical and chemical structure of the food. Cooking is essentially a heat-transfer process, in which the inflowing energy alters food properties. Common cooking processes differ in how the energy is transferred, what parts of the food are most affected, and how rapidly and how much the food's properties change. Understanding the subtle differences between the several distinct ways of applying heat to food is one of the marks of a gourmet chef!

Outline

- I. Most foods are best stored at temperatures just a few degrees above the freezing point of water. Low temperature slows the enzymatic chemical reactions that alter the food's properties. It also inhibits the growth of bacteria—both those that spoil the food and pathogens, which, although they may have no obvious effect on flavor, can result in serious disease when ingested.
 - A. Even the rough difference of 30 °F between room temperature and the interior of a refrigerator has a dramatic effect on the time food can be kept without spoiling. Fresh milk, for example, keeps about two weeks at refrigerator temperatures; it would spoil in a few hours at room temperature.
 1. The remarkable effect of a few degrees' temperature difference lies in the molecular energy that is the basis of heat-related phenomena. At any temperature, there's a wide range of energies, with the average being an indicator of the temperature.
 2. The relatively few molecules with the most energy, however, are most responsible for driving chemical and biochemical reactions. Raising the temperature slightly doesn't change the average energy very much, but it greatly increases the number of high-energy molecules. Hence, reaction rates increase dramatically—including food spoilage.
 - B. Domestic refrigerators work on a principle discussed in the previous lecture—namely, that it takes energy to change the state of a substance from liquid to gas.
 1. The refrigerator contains a *working fluid* whose liquid-gas transition occurs at a temperature somewhat below the lowest

temperature desired in the refrigerator. Early refrigerators used ammonia, a material that was hazardous if it leaked. In the 1930s, a synthetic chemical called Freon replaced ammonia. In the 1970s, scientists discovered that Freon and related chemicals destroyed the protective ozone layer high in Earth's atmosphere, and by the 1990s, the use of Freon was phased out in favor of newer, less harmful synthetic materials.

2. A motor-driven pump compresses the working fluid, at this point in gaseous form, raising its pressure and temperature. The fluid then passes through tubing exposed to the environment outside the refrigerator. This cools the fluid, which condenses into a liquid.
 3. The high-pressure liquid passes through an expansion valve, basically just a constriction in the piping, greatly reducing its pressure.
 4. The low-pressure fluid passes through tubing exposed to the interior of the refrigerator. As it does so, it evaporates. The energy required to change the fluid from liquid to gas comes from the refrigerator's contents, which, therefore, cool.
 5. The fluid is once again condensed and the process is repeated. During the condensing process, the energy that was extracted from the refrigerator contents is transferred to the refrigerator's surroundings. Thus, the refrigerator "pumps" heat from its interior to its surroundings. Unfortunately, it consumes energy in the process—much more about this in the next lecture.
- II. Conventional cooking systems are much simpler than refrigerators—for profound reasons that I'll cover in the next lecture. Electric ranges convert electrical energy into heat by passing current through resistive wires. Gas ranges use the heat released in combustion of natural gas or propane. Either way, the purpose of cooking is to alter food characteristics to enhance flavor and texture and to kill harmful bacteria.
 - A. Cooking involves a number of complex chemical and physical changes. Proteins in meat and other animal products coagulate when heated, making the food firmer and, if carried to extremes, tough. Reactions between sugars and amino acids generate hundreds of different flavor-enhancing substances. Heating, especially in the presence of water, breaks down complex sugars into simpler molecules and, at high enough temperatures, results in caramelization. An important goal of cooking is to exert some control over these processes. Different cooking methods use combinations of the three basic heat-transfer mechanisms—conduction, convection, and radiation.
 - B. In baking, boiling, simmering, deep-fat frying, and similar methods, food is immersed in a hot medium—air, water, or oil—and energy flows from the medium into the food until it reaches the desired

temperature. In all these cases, energy is deposited on the outside of the food, then makes its way to the interior by conduction.

1. In baking, electric elements or gas flames heat the air in the oven. Convective air circulation transfers energy throughout the oven, heating the air and oven walls. Convection also carries energy to the food. Because air has a low heat capacity, the air near the food drops in temperature as it gives energy to the food. Air's low heat capacity is the main reason that baking is a rather slow process. In *convection ovens*, a fan forces a more rapid air circulation, keeping the air near the food warmer and, thus, reducing cooking times. Rapid convection also results in a more even temperature distribution in the convection oven.
2. In boiling and simmering, conduction carries heat from an electric or gas burner through a pan and into water. Convection in the water then carries heat to the food. Because of water's great heat capacity, boiling is more rapid than baking. Boiling in an uncovered or loosely covered pot ensures that the water temperature is the boiling point, or 212 °F (100 °C). In a pressure cooker, the higher pressure results in a higher boiling point—typically 250 °F, with double atmospheric pressure; therefore, food cooks faster (recall the phase diagram of the previous lecture).
3. In steaming, food is immersed in water vapor over boiling water. Energy is transferred to the cooler food as water vapor condenses on the food and gives up its latent heat. Again, the temperature is held at water's liquid/gas transition point of 212 °F.
4. In a double boiler, excellent for gently cooking egg custards, a second pan holding the food is suspended above boiling water. Water vapor condenses on the bottom of the pan, giving up its latent heat and maintaining a uniform 212 °F. Because it involves no violent convective motion, this is a much gentler method of cooking.
5. Deep-fat frying is similar to boiling, but because fat can be heated well above the boiling point of water, cooking times are typically much shorter.

C. In grilling and broiling, heat is transferred directly to the food.

1. In panbroiling, stir-frying, and griddle cooking, the hot pan itself is the heat source, and heat transfer is by conduction into the food.
2. In broiling and grilling, heat transfer is by radiation from hot coals or an oven's heating element.

III. Microwaving is an entirely different cooking method.

- A. Strictly speaking, microwaving itself does not involve heat. Pause and consider why not. Remember the precise definition of heat: energy being transferred as a result of a temperature difference. In microwave cooking, there's no temperature difference; the source of the

microwaves (the magnetron; recall Lecture Eighteen) is not particularly hot compared with the food. Microwaving is, therefore, a *nonthermal* method of energy transfer.

B. Microwaves cook because the oscillating electric field of the microwaves acts on molecules that, although electrically neutral, have uneven distributions of electric charge. The water molecule has a particularly pronounced charge distribution, with the oxygen atom more negative and the two hydrogen atoms more positive. Thus, water and water-containing foods are particularly efficient absorbers of microwave energy. Many other substances, such as glass, most plastics, and paper, are not—which is why you can boil water in a paper cup in a microwave oven.

1. The microwaves in an oven are electromagnetic waves of a specific frequency and, therefore, wavelength. The frequency is about 2.4 billion cycles per second (2.4 gigahertz), and the corresponding wavelength is about 12 centimeters or 5 inches. The walls of the oven, behind the typical plastic interior, are metal, so the microwaves reflect and fill the entire oven. The reflected waves interfere, producing regions of constructive (high microwave intensity) and destructive interference (low intensity). If the wavelength were very short (as it is for light), these would be so close as to be unnoticeable. But because the wavelength is significant compared with the size of common food items and the oven itself, regions of constructive and destructive interference are typically a few inches apart.
2. This interference pattern could lead to uneven cooking of food. That's why food in a microwave oven rides on a rotating platform—the idea being to ensure that no part of the food remains long in a “cold spot.” In some ovens, the food is stationary, but a rotating metal reflector above the roof of the oven “stirs” the incoming microwaves to keep the interference pattern changing.
3. Microwaves are kept safely in the food by a metal screen embedded in the glass window. As long as the holes in the screen are small compared with the wavelength, very little microwave energy escapes.
4. Unlike other cooking methods that deliver energy to the food surface, microwaves actually penetrate the food. Typical penetration depth is about half an inch. Microwaves heat the food to about this depth, and conduction from the heated outer layer transfers heat further in.
5. Many foods benefit from cooking at low power, which in a microwave oven is accomplished by turning the microwaves alternately on and off. This gives thermal conduction time to distribute the energy more evenly throughout the food.

6. Microwaving is not particularly effective on ice, because the water molecules in ice are locked into the structure of the ice crystal and cannot easily respond to the microwave electric field. That's why thawing foods in the microwave is done at low power, with the microwave energy being absorbed by other molecules, then transferred by thermal conduction to the ice.

7. Microwaving is very efficient, in that virtually all the microwave energy generated in the oven ends up in the food; there's no heat escaping to the environment. But a typical oven converts only about half of the incoming electrical energy to microwaves, so its overall efficiency is less.

C. Microwave cooking entails some unique dangers.

1. The electric fields in microwaves cause electric currents to flow in metals, resulting in heating that may actually melt the metal.

2. At sharp corners, electric charge can accumulate on metals, resulting in huge electric fields and sparking that can damage utensils or the oven itself or even start a fire. Even something as small as the metal staple on a tea bag can cause problems.

3. An empty microwave oven is hazardous to itself; with nothing to absorb the microwaves, the energy ultimately returns to the magnetron, where it may cause damage.

4. Because microwaving heats water from the outside in, boiling water in a microwave does not result in vigorous convection. It's possible for the water to become *superheated*, exceeding the boiling point but not boiling. The slightest disturbance—like removing a mug of water from the oven—can then trigger dangerously explosive boiling.

IV. The perfect soft-boiled egg: a simple kitchen task?

A. Egg-white proteins begin to coagulate at 63 °C (about 145 °F), while yolk proteins coagulate at about 15 °F higher. A perfect soft-boiled egg must be heated so that its white exceeds 145 °F but not by so much that the yolk gets a lot hotter.

B. Heat transfer into the egg depends on its size, its initial temperature, and the water temperature. Although this isn't a mathematical course, it's amusing to present a scientific formula giving the time for the yolk to reach a given temperature. Good chefs instinctively know this without doing the math!

Suggested Reading:

Robert L. Wolke, *What Einstein Told His Cook: Kitchen Science Explained*.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, pp. 299–302.

Going Deeper:

Peter Barham, *The Science of Cooking*.

Questions to Consider:

1. Why should you leave the oven door ajar when broiling?
2. It takes exactly twice as long to cook two portions of food in a microwave oven as opposed to one but not significantly longer in a conventional oven. Why the difference?

Lecture Twenty-Nine

Like a Work of Shakespeare

Scope: The *second law of thermodynamics* occupies a unique place in physics, with applications ranging from everyday experience to the ultimate fate of the cosmos. Unlike other physical laws, the second law is not about what must happen but, rather, about what is unlikely to happen. The essence of the second law is that order inevitably evolves into chaos. The concept of *entropy* quantifies this notion; thus, the second law becomes a statement that entropy generally increases—and, in any event, can never decrease. The second law's consequences for heat and energy are especially significant. The second law makes it impossible for us to extract all the random thermal energy in an object and convert it to more useful forms, such as electrical energy or the energy of motion. That means we can't build perfectly efficient engines, power plants, or other devices that extract energy from heat sources. It also means we can't build a perfect refrigerator—any refrigerator needs an external energy source. Ultimately, the second law is about the *quality* of energy rather than its quantity. So important is the second law that British writer C. P. Snow compared ignorance of the law with not having read a work of Shakespeare!

Outline

- I. We're not quite done with physics in the kitchen! Here's a simple culinary act: Break an egg and beat it. Now, if I carefully retrace the steps of the beater, can I once again separate egg and yolk? Of course not! And that's the essence of the *second law of thermodynamics*.
 - A. There's nothing in the usual laws of physics (Newton's laws of motion, Maxwell's laws of electricity and magnetism) that would prevent the egg from reassembling. It's just extraordinarily unlikely. Of all the possible ways the egg molecules could be arranged, the number of arrangements with all the yolk molecules together is almost infinitesimally tiny compared with arrangements in which white and yolk molecules are intermixed. Given a random beating, then, it's extremely unlikely that the beaten egg will spontaneously separate into yolk and white. How unlikely? So unlikely that if I repeated the experiment every minute for the 15-billion-year age of the Universe, separation of white and yolk would still be extremely unlikely.
 - B. There are numerous other examples of this concept.
 1. Whoops! I dropped my note cards. If I simply scoop them up, what is the chance that I'll get a coherent lecture? Almost zero. Again, chaos triumphs over order.

2. I shove a block of wood along the table. It soon comes to a stop because the force of friction (Lecture Eight) opposes its motion. We don't see this, but it also gets warmer as friction converts its ordered motion into the random thermal motion of molecules in the block and the table. A sensitive thermometer stuck in the block would show this, and a movie of the block sliding to a stop and the temperature rising would make perfect sense. But shown in reverse, the movie would look absurd. We never see all the molecules in a stationary object suddenly move in the same direction, giving the object a bulk motion! But that wouldn't violate Newton's laws, or the conservation of energy, or any other "ordinary" law of physics; it's just extremely unlikely.
3. Put a glass of hot water and a glass of cold water in contact in an insulated container. After awhile, they're both lukewarm, because energy has moved by thermal conduction from the hot to the cold water. Wait a while longer, and they're still lukewarm. You'll never come back to find once again glasses of hot and cold water side by side—although energetically that's possible.

- II. All these examples illustrate the second law of thermodynamics. In each case, we begin with an ordered state—separate egg white and yolk; note cards organized into a coherent lecture; a block of wood with its molecules sharing a common motion; and water with faster moving molecules all in one glass, slower moving molecules in another. We end with a less ordered state—a scrambled egg, a random stack of note cards, random thermal motion only, and two glasses of lukewarm water. In all cases there's no going back—at least not spontaneously—simply because the ordered states are so rare, so improbable.
 - A. The concept of *entropy* distinguishes the ordered from the disordered states. Entropy is a precisely defined mathematical quantity that increases with increasing disorder. The ending state in each example is a state of higher disorder and, thus, higher entropy.
 - B. In its broadest form, the second law states that the entropy of a closed system can never decrease. A closed system means one that is isolated from its surroundings, with neither matter nor energy flowing into or out of the system. The ultimate closed system is the Universe itself, and in its most cosmic form, the second law thus states that the entropy of the Universe can never decrease. Most processes—such as beating an egg or creating friction—are imperfect in the sense that they result in an irreversible entropy increase.
 1. That closed-system stipulation is important. Locally, entropy can decrease—meaning a system can become more organized. But this can only happen if energy flows into the system. Consider two examples:

2. Put a glass of lukewarm water in the refrigerator. Eventually, it gets cooler and the refrigerator's external surroundings get a bit warmer, as the refrigerator "pumps" energy out of the water and rejects it to its surroundings (recall the discussion of refrigerators in the previous lecture). This sounds like the situation I just said was impossible, especially if you put another glass of water against the refrigerator's warm exterior coils so that it warms up. Taken in isolation, the system of the two water glasses does indeed get more organized and, therefore, its entropy decreases. But this only happens because the refrigerator is plugged in, using electrical energy. Expand the system to include the refrigerator and the electric power plant that generates the electricity, and you'll find that the entropy of that system increases, as the second law requires.

3. The appearance of life on Earth, the growth of a plant from randomly distributed molecules of soil and air, my sorting my notes back into a coherent lecture, the appearance of a book from what were randomly distributed molecules of ink, and the development of human civilization—all these are processes that convert random arrangements of matter into highly organized ones. Thus, all reduce entropy—on Earth, that is. But Earth, like the refrigerator, is "plugged in"—in this case, to the Sun, through the steady stream of solar energy that powers life on our planet. Enlarge the system to include the Sun, with the energy-generating nuclear reactions at its core, and you'll find that the entropy of the Earth-Sun system increases. We gain organization on Earth at the expense of more disorganization in the Sun.

C. A narrower but equivalent statement of the second law reads: *It is impossible to build a perfect heat engine.* A heat engine is a device that converts random thermal energy into more useful forms, such as motion or electricity. In this form, the second law says that you can't convert all the thermal energy in a system to useful forms; some of it must remain random. This has profound implications for the use of energy in our technological society. I'll elaborate in the next lecture.

1. The second law is about energy *quality*. Random thermal energy is of lower quality than the energy of directed motion or electricity. You can convert the energy of an object's directed motion to thermal energy, but you can't go the other way with 100 percent efficiency.

2. Even thermal energy comes in different qualities; high temperature represents higher quality. You can extract some useful nonthermal energy from the system consisting of separate quantities of hot and cold water (you'll see how in the next lecture); once they're mixed, that possibility is gone. The greater the temperature difference, the greater the quality of energy (and the lower the entropy). In all

these cases, I'm talking about the same *quantity* of energy but different energy *quality*.

D. Another equivalent statement of the second law reads: *Heat won't flow spontaneously from a cooler object to a warmer object*, or more technically: *It is impossible to build a perfect refrigerator.* That's simply a restatement of my example of the two glasses of lukewarm water that won't spontaneously organize themselves into hot and cold—even though there's sufficient energy in the water. A real refrigerator is imperfect, needing a source of additional energy.

1. Back to the kitchen: This is the reason why I said a stove is a much simpler device than a refrigerator; the former easily converts high-quality electrical to low-quality thermal energy with 100 percent efficiency, while the latter has to use a complex mechanism to overcome—only locally!—the second law's prohibition on heat flowing from cooler to hotter. That complicated mechanism, and the energy with which it's supplied, eliminates the word *spontaneously*; therefore, there's no violation of the second law.

2. Refrigerators and heat engines are inverse devices. More on this in the next lecture.

III. Why the Shakespearean title? And why all this talk of the *second* law of thermodynamics? What happened to the first?

A. In 1959, C. P. Snow, a British scientist (molecular physics), novelist, and government official, wrote *The Two Cultures*, in which he decried the split between the sciences and the humanities. Snow singled out the second law of thermodynamics as an example of science that every educated person should know; he likened it to a work of Shakespeare—hence my title.

B. The second law implies there must be a first law. The *first law of thermodynamics* states simply that energy is conserved—although it may be transformed among different forms, including the mechanical energy of bulk motion and random thermal energy. More specifically, the first law says that the internal or thermal energy of an object may be changed either by heat flow or by doing mechanical work. Thus, the first law is about energy *quantity* while the second is about its *quality*. Much more on this in the next lecture!

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 18, especially p. 355 onward.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, pp. 297–298.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapter 22, sections 1 and 5.

C. P. Snow, *The Two Cultures and the Scientific Revolution*.

Questions to Consider:

1. Give two examples from everyday life in which entropy increases.
2. Conservation of energy is a fundamental law of physics. If energy is conserved, why are we so concerned about using it efficiently?

Lecture Thirty

Energy in Your Life

Scope: Modern humanity uses energy at a prodigious rate. The human body produces energy at the rate of about 100 watts, the equivalent of a 100-watt lightbulb. The average citizen of the United States uses energy at the rate of about 100 human bodies' worth—as if we had 100 “energy servants” working for us round the clock. Most of that energy comes from burning fossil fuels; much of the rest is from nuclear sources and from the burning of garbage, wood, and other biomass. All these involve thermal energy and are subject to the laws of thermodynamics. Some of our energy use is of the highest quality, or lowest entropy. This includes energy used in transportation and electrical energy. Other energy uses call for lower quality energy, as in space heating, water heating, and some industrial processes. The second law of thermodynamics puts stringent limits on our ability to extract high-quality energy from thermal sources. As a result, our electric power plants are typically only 30 to 40 percent efficient, and our cars and trucks, only about 25 percent efficient. We could use energy more efficiently if we paid increased attention to the concepts of entropy and energy quality.

Outline

- I. Modern humanity uses energy at a much greater rate than our bodies can provide. The hand-cranked generator shows that the human body can produce energy at a sustained rate of about 100 watts. Deep knee bends at about once a second produce energy at about the same rate.
 - A. We need to distinguish energy and power. *Energy* is the actual amount of “stuff,” while *power* is the rate at which it's used or produced. Common units of energy include joules, calories, British thermal units, and kilowatt-hours. Common power units include watts and kilowatts, horsepower, and Btu/hour. Energy and power are often confused. To say that the average power output of the human body is 100 watts is to give the rate at which the body produces energy. The total amount it produces depends on how long it's producing at this rate.
 - B. The average U.S. citizen of the early 21st century uses energy at the rate of about 10,000 watts—10 kilowatts (kW), or 100 times the body's rate of energy output. That's like having 100 “energy servants” working for each of us round the clock. (The number is less in most but not all other countries; in Western Europe, it's about 50 “energy servants.”)

- C. Those energy servants perform a lot of useful services, including, broadly, transportation, industry, and residential and commercial energy supply.
 - D. Most of that energy comes from burning fossil fuels. Much of the rest is from other thermal processes, including nuclear fission and the burning of garbage or biomass.
- II. To extract useful, high-quality energy from thermal sources, we use *heat engines*. Examples include the gasoline and diesel engines that power our vehicles, jet engines used in aircraft, old-fashioned steam engines, and the steam boilers and turbines used in electric power plants.
- A. Conceptually, all heat engines operate in much the same way, going through a sequence of steps that typically involve expansion, compression, and/or state change of a fluid.
 1. Heat flows into the fluid, which expands, pushing on a piston and producing high-quality mechanical energy.
 2. The heat flow stops and the fluid continues to expand, now cooling. More mechanical energy is produced.
 3. To get the fluid back to its original state, it's cooled and compressed. During this phase, heat flows from the fluid to the environment; thus, some of the energy that originally entered the fluid is lost as waste heat, rather than being turned into mechanical motion.
 4. The fluid is isolated from the environment and continues to compress to its original state. The cycle then repeats.
 - B. Although real heat engines use different processes, they all share the common phases of heating, expansion, cooling, and compression—and all involve turning some but not all of the energy from a thermal source into high-quality mechanical energy.
 1. Examples include gasoline and diesel engines, in which heating and expansion are associated with fuel burning in a cylinder, and steam power plants, in which heating by fossil or nuclear sources turns water to steam, which then drives a turbine. A car's radiator and a power plant's cooling towers all emphasize the fact that some energy is lost as waste heat.
 2. Couldn't a clever engineer design a more efficient heat engine that didn't have to waste any energy? No! In 1824, the French physicist Sadi Carnot proved that no heat engine can be more efficient than the *Carnot engine* that I described above and that the efficiency of this engine is limited by the ratio of the minimum to maximum temperatures involved in the engine. The greater the extremes of temperature, the more efficient the engine. An engine with 100 percent efficiency would require either an infinite high temperature or absolute zero low temperature—both of which are impossible.

3. We're stuck with Earth's ambient temperature at the low end, and the strengths of typical materials limit high temperatures, with the result that typical heat engines have efficiencies in the 25–40 percent range; even the most advanced barely exceed 50 percent. That means we throw away somewhere between half and three-fourths of the energy we extract from fuels.
 4. That isn't just waste but may also cause *thermal pollution*. For example, a substantial fraction of the total river flow in the United States makes its way through the cooling systems of electric power plants, raising water temperatures and potentially affecting river ecology.
 5. Couldn't we do something with that waste heat? Yes! Stay tuned.
- III. Energy uses can be distinguished by the quality of energy that's needed.
- A. Some energy uses require relatively low-quality energy. These include space heating, water heating, and some industrial processes.
 1. Such energy can be produced directly by burning of fuels, as in a home heating system, water heater, or industrial boiler. About two-thirds of the energy need in the United States is for such low-quality energy.
 2. Most of the energy produced in burning can be captured and used to heat water, air, or other substances. Thus, direct burning is fairly efficient and could supply our low-quality energy needs. The second law of thermodynamics places no restriction on such energy conversion.
 - B. Transportation and electrical energy for motors, lights, and electronic equipment require high-quality (low-entropy) energy. These uses make up about one-third of our energy needs. Again, the second law of thermodynamics says we can't convert from thermal energy to high-quality energy of motion or electricity with 100 percent efficiency.
 - C. Although we need high-quality energy for only about one-third of our energy uses, about two-thirds of the energy we produce is of the highest quality. Therein lies huge inefficiency and energy waste.
 1. Consider domestic water heating. Some homes burn gas or oil to heat water, either in a separate heater or as part of the home's space heating system. But many use electric water heaters. A good gas heater recovers about 80 percent of the fuel energy to use in heating the water; for an electric heater, the figure may be as high as 95 percent of the incoming electrical energy ending up as thermal energy in the water. But which is really more efficient? Pause and think about this! Assuming the electricity is produced in a power plant with a typical efficiency of only about 35 percent, the electric heater is much less efficient.

2. All that waste heat from our power plants could be used to supply low-quality energy needs. That's done in some countries, where waste heat from central power plants has been piped to the surrounding communities for heating. More recently, energy deregulation has favored the practice of *cogeneration*, whereby industries and other large institutions generate their own electricity and simultaneously use the waste heat, often in the form of steam, for processes requiring lower quality energy. Europe, the world leader in cogeneration, is approaching 30 percent cogenerated electrical energy.

IV. Another approach to more efficient energy use is to employ *heat pumps*, of which refrigerators and air conditioners are examples. With these, we're generally concerned with cooling, but conceptually, a refrigerator or air conditioner is simply a device that pumps heat energy from cooler objects (the refrigerator contents; a room or house) to a warmer ambient environment (recall the previous lecture).

- A. Run an air conditioner in reverse and you have a heat pump, extracting heat from the cooler outdoor environment in the winter and pumping it into a house. In the southern United States, the same device is used for cooling in the summer and heating in the winter, exchanging heat between the house interior and the outside air. In northern climes, it's more efficient to exchange heat with the ground, through a system of buried pipes.
- B. A heat pump is, conceptually, a heat engine going in reverse. An engine extracts energy from a hot source and delivers high-quality mechanical energy as well as waste heat rejected to a lower temperature environment. A heat pump takes in both energy from a low-temperature environment and high-quality energy (for example, electricity used to run a refrigerator's compressor) and delivers energy to a higher temperature environment.
 1. Applied to heat pumps, the second law of thermodynamics says that the greater the temperature difference between low- and high-temperature regions, the more high-quality energy must be supplied.
 2. For example, a heat pump extracting energy from the ground at 50 °F and delivering it to a water heater at 150 °F requires, in theory, just one unit of electrical energy for every six units of energy supplied to the water. Thus, a heat pump can be much more efficient than direct use of electricity or even than burning of a fuel.

V. The examples in this lecture represent some ways to reduce the huge number of "energy servants" at our beck and call. All are based on understanding the important limitations posed by the second law of thermodynamics. But these are only a few of the many ways we might reduce our use of energy and/or

increase the efficiency with which we use energy. Could we get away with 50 energy servants instead of 100? There's enough in that question for another whole course!

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 18, especially pp. 349–352.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 7, section 1, especially pp. 299–302.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff. *Physics for Scientists and Engineers*, chapter 22, sections 2 and 3.

Questions to Consider:

1. On a cold morning, some folks will turn on the oven and leave the door open to help warm the house. Not a very safe practice, but it works. On a hot day, could you cool the house by leaving the refrigerator door open? Explain your answer.
2. In the heat-pump example in this lecture, you use one unit of electrical energy and end up with six units of energy supplied to heat water. Where did the extra energy come from?

Module Six: Potpourri

Lecture Thirty-One

Your Place on Earth

Scope: This module begins with “Your Place on Earth” and ends with “Your Place in the Universe.” That final lecture is a grandiose look at your intimate physical connection to the broader Universe and its evolution. This first lecture is, in contrast, technologically specific. Here *place* means *position*—specifically, how you can know your exact position on Earth. Space technology, in the form of the Global Positioning System (GPS), provides the answer. GPS is an increasingly pervasive and, in some cases, invasive technology. Originally developed for military purposes, GPS is now used routinely for sea, air, and even automobile navigation; for tracking vehicles, freight, animals, and people; and increasingly, for emergency location of 911 calls from cell phones. GPS also aids surveyors, geologists, environmental scientists, oceanographers, and others in studying our planet. The system represents a remarkable confluence of physics-based technologies, from orbiting satellites to the exquisite timekeeping of atomic clocks. In the coming years, GPS will almost certainly play an increasingly important role in your life.

Outline

- I. In space, GPS consists of a “constellation” of nominally 24 satellites, in orbits about 12,000 miles above Earth, where the orbital period is 12 hours. At this altitude, there is essentially no air resistance; thus, the satellites’ orbits and, hence, positions are known with exquisite accuracy.
 - A. The relative positioning of the orbits means that every point on Earth can always see at least four satellites.
 - B. The satellites’ exact orbits are monitored from the ground, and updates are frequently sent to the satellites. The satellites continually broadcast their precise positions, as well as the time.
 - C. GPS satellites have lifetimes of about 7–15 years, and older satellites are regularly replaced by new ones with enhanced capabilities.
- II. GPS works by measuring the distances from satellites to a given GPS receiver. You may once have learned to determine distances by triangulation from a known position; GPS is somewhat the opposite, getting position from distances.
 - A. Knowing the distance to one satellite tells us that we’re somewhere on a sphere whose radius is that distance (in two dimensions, the sphere would be a circle).

- B. Knowing the distance to two satellites tells us that we’re on the intersection of two spheres—namely, somewhere on a circle (on one of two points in two dimensions).
 - C. Adding the distance to a third satellite narrows the choice of position to just two points—one of which can usually be rejected because it makes no sense.

- III. Distances are determined by accurately measuring the time it takes radio signals, moving at the speed of light, to travel from satellite to receiver.
 - A. If both satellite and receiver had perfectly accurate clocks, signals from three satellites would suffice to determine position.
 - B. The satellites have extremely accurate (and expensive!) atomic clocks on board.
 1. Atomic clocks are based on the frequency of light emitted as electrons jump from one atomic energy level to another. One second is defined as exactly 9,192,631,770 cycles of the light emitted or absorbed in a particular electron transition in the element cesium. The atomic energy levels used are very close, corresponding to so-called *hyperfine transitions*, and the associated frequencies are in the microwave region of the electromagnetic spectrum. Atomic clocks use cesium or other elements to implement an atom-based time standard.
 2. The clocks used in GPS satellites are typically accurate to about 10 billionths of a second, and each satellite carries four clocks. Because of its satellite-based atomic clocks, GPS can be used to determine time as well as position.
 3. Each satellite sends out a unique signal consisting of a seemingly random (“pseudo-random”) string of digital 1s and 0s. The receiver generates its own versions of these signals, which should be in sync with the satellites’ s, but because of the distances to the satellites, there are delays. Measuring those delays determines the distances.
 - C. GPS receivers would be prohibitively large and expensive if they contained atomic clocks; for this reason, they contain less accurate clocks.
 1. As a result, position measurements based on three satellites are not accurate.
 2. GPS receivers use measurements from a fourth satellite to correct for receiver clock errors. Because three perfect measurements alone would fix the receiver’s position, any inconsistency with a fourth measurement contains information about the receiver’s clock errors; with the fourth measurement, then, those errors can be corrected.

3. The result is a measurement of position on Earth that's typically good to tens of feet and can, under some circumstances, be accurate to mere inches.
- D. In addition to position, GPS receivers also determine relative velocity between the receiver and satellite using the Doppler effect (Lecture Six). This permits faster and more accurate calculation of the receiver's motion.
- IV. The GPS system corrects for a number of other errors, some trivial and others profound.
- A. The satellites's locations are known but not perfectly. Position predictions are updated approximately each hour and are typically good to a few meters, or about 10 feet.
 - B. Because the satellite clock times are typically good to about 10 billionths of a second and because light travels about 1 foot in a billionth of a second, clock errors introduce a distance error comparable to the 10-foot error in satellite position.
 - C. Earth's upper atmosphere, or *ionosphere*, contains electrically charged particles (in particular, electrons) in varying abundances. These alter the speed of the radio signals from GPS satellites and, thus, the calculated satellite distances. Although knowledge of atmospheric conditions can help correct these errors, the most sophisticated correction comes from the fact that different radio frequencies are affected in different ways. GPS satellites broadcast on two separate frequencies, and by comparing the arrival times of the two frequencies, a receiver can reduce this error to approximately 15 feet.
 - D. GPS signals may reach the receiver directly or after reflection from water, buildings, or other objects (this same phenomenon causes "ghost" images in TV pictures). Calculating distance based on a reflected signal would lead to error. Furthermore, these "multipath" signals interfere with each other. GPS receivers use sophisticated schemes for determining which signal arrives first, in an attempt to use only information from the direct signal. Multipath error typically amounts to about 2 feet.
 - E. A particularly fundamental source of potential error arises because of Einstein's special and general theories of relativity. According to the special theory, the relative motion of satellites and observers means their clocks are not measuring the same time. The general theory deals with gravity, and in the GPS context, it says that time at the satellites's altitude runs faster than on the ground. Both these effects must be taken into account, or GPS measurements would be off, in a day's time, by close to a mile.

- F. *Differential GPS* is used in precision applications to reduce errors still further. Differential GPS uses two GPS receivers that may be up to a few hundred miles apart.
 1. One receiver is placed at a fixed point whose location is accurately known. The second roving receiver is then used to make measurements relative to the first.
 2. Because the receivers are fairly close, signals reach them through the same atmospheric path; therefore, atmospheric errors are the same. Given that one receiver is in a precisely known location, the discrepancy in timing due to the atmosphere can be determined and accounted for in the roving receiver.
 3. Similarly, the fixed receiver can determine the clock and position errors for the individual satellites and relay this information to the roving receiver.
 4. The use of differential GPS essentially eliminates clock and position errors and reduces other errors to a few feet. More sophisticated differential GPS techniques can push errors down to a few inches.
- V. GPS is widely used in a variety of applications; here, we sample just a few.
- A. GPS reception is increasingly built into cell phones to provide 911 emergency location information, as well as commercial enhancements, such as providing phone numbers of nearby restaurants, as determined by the phone's GPS location.
 - B. Hand-held GPS receivers provide position information for hikers, boaters, and others. Coupled with built-in map software, these units display the user's position as a location on a map.
 - C. GPS navigation systems in cars use GPS to monitor continuously the car's location. The information is combined with optimizing software, digital road maps, and computer voice technologies to determine the best route to a desired destination, then to provide real-time voice and/or visual instructions at each turn. In tunnels or when tall buildings obscure the GPS satellites, a less accurate system based on the vehicle's odometer and acceleration sensors temporarily keeps track of position.
 - D. In GPS vehicle-tracking systems, a GPS receiver on each vehicle relays the vehicle's position to a central monitoring station. Uses include tracking freight-carrying trucks, deploying emergency vehicles and taxis efficiently, and even determining if rental cars stray beyond their allowed boundaries. Anxious parents or covert operatives can install GPS receiver/recorder units surreptitiously, later downloading detailed logs of a vehicle's travel, including street names!
 - E. In farming, GPS guides tractors to accuracies of an inch or so, reducing fuel consumption and time involved in plowing. Uses like this require differential GPS, but because only relative positions are important, the

fixed GPS need not be at an accurately known location. A similar technique is used to guide heavy construction equipment.

- F. Because GPS gives altitude as well as longitude and latitude, it's ideally suited for aircraft navigation. Use of GPS can help alleviate air traffic congestion, allow more efficient flight paths, and augmented by ground-based systems, bring all-weather capability to smaller airports.
- G. GPS has many uses in science and engineering. Here are a few:
 - 1. Using differential GPS, geologists monitor the flow of glaciers and even the growth of mountains.
 - 2. Oceanographers measure the scattering of GPS signals off the ocean surface and use the result to calculate wind speeds at the ocean surface.
 - 3. Engineers monitor deformation in such structures as dams and bridges, again, using differential GPS to provide inch-level accuracy.
 - 4. Wildlife biologists place GPS collars on large mammals to monitor ranging behavior and herd migration. The devices can log months worth of data for later analysis.
- H. Although you may not realize it, GPS is probably already an example of physics in your everyday life. And GPS will only become more prevalent in the future.

Suggested Reading:

Marshall Brain, *Marshall Brain's How Stuff Works*, pp. 91–93 and 95.

Per Enge, "Retooling the Global Positioning System," *Scientific American*, May 2004, pp. 91–97.

Going Deeper:

Ahmed El-Rabbany, *Introduction to GPS: The Global Positioning System*.

Bruce Grubbs, *Using GPS: GPS Simplified for Outdoor Adventurers*.

Questions to Consider:

- 1. Measurement of the distances to three satellites should be enough to fix one's position. Why, then, must GPS receivers "see" a minimum of four satellites?
- 2. Should accurate GPS signals be provided, as they are today, essentially freely to anyone on Earth?

Lecture Thirty-Two

Dance and Spin

Scope: Many objects, from electrons to dancers and skaters, CDs to wheels, planets to stars and galaxies, undergo rotational motion. Although such motion could be described in terms of Newton's laws, it would be difficult to characterize the different speeds and directions of all the parts of a rotating object. Consequently, physicists describe rotational motion in terms uniquely suited to the phenomenon of rotation. These terms are analogous to the corresponding terms for ordinary straight-line motion, and a corresponding set of laws describes them. But applied to rotation, these laws lead to some surprising new phenomena that occur throughout the realms of physics, including such everyday applications as bicycle riding, ice skating, and weather. Rotation can even provide a remedy for the apparent (but not actual!) absence of gravity in orbiting spacecraft.

Outline

- I. When an object rotates, different parts of it move with different speeds and in different directions. In this situation, it's convenient to describe the rotation using quantities that apply to the entire rotating object.
 - A. *Angular velocity* measures the rate at which an object rotates. As with ordinary velocity, it has a direction as well as a numerical value. That direction is given by curling the fingers of your right hand in the direction of the rotation; then your right thumb points in the direction of the angular velocity.
 - B. Just as mass is a measure of how hard it is to change an object's motion, so *rotational inertia* measures how hard it is to change rotational motion. The rotational inertia of an object depends not only on its mass but also on how that mass is distributed relative to the axis of rotation.
 - C. Just as momentum is the product of mass and velocity, so *angular momentum* is the product of rotational inertia and angular velocity. And just as the momentum of a system is conserved if no external forces act on it, so the angular momentum of an isolated system is conserved. This fact has remarkable consequences from the atomic scale to everyday happenings to the cosmic realm.
 - 1. Because angular momentum has direction as well as numerical value, the spin axis of an isolated spinning object will remain in a fixed orientation. This is the principle of the *gyroscope*, long used for navigation in vehicles ranging from submarines to ships to missiles. Gyroscopes are also used to stabilize systems that would otherwise be subject to excessive sway or vibration. Examples

include cameras, telescopes, satellites, and cruise ships. A recent application is the use of micro-miniaturized gyroscopes in some GPS receivers (previous lecture!) to maintain location information if the GPS satellite signal is temporarily lost.

2. Change the rotational inertia of an isolated system, by redistributing its mass, and the rotational velocity must change to keep its angular momentum unchanged. Dancers and skaters routinely exploit this phenomenon to spin at high rates. Starting with arms extended, they go into a slow spin. Pulling in the arms greatly reduces the rotational inertia. To keep angular momentum unchanged, the rotation rate must increase. A cosmic application of this phenomenon is the *pulsar*, a rapidly spinning object with the mass of a star packed into a volume just a few miles across. Pulsars form when a star explodes as a supernova, collapsing much of the stellar material and, to conserve angular momentum, greatly increasing the spin rate. The fastest pulsars have been clocked at some 600 rotations per second.
3. Change the angular momentum in one part of a composite system, and other parts must respond to keep the original angular momentum constant. This phenomenon is used to steer the Hubble Space Telescope and many other satellites. Instead of using rockets, which would eventually run out of fuel and whose exhaust would interfere with Hubble's exquisite vision, the spacecraft includes three motorized wheels mounted in three perpendicular directions. Starting one wheel sets the telescope spinning in the opposite direction; stop the wheel and the telescope stops. In this way, the telescope can be made to point in any direction. Because the motors run on electricity generated by solar panels, there's no fuel to run out.

II. The rotational analog of force is *torque*, which describes the effect of a force applied at some distance from a rotation axis. Just as force produces *change* in motion (Newton's second law), so torque produces *change* in rotational motion—specifically, in angular momentum.

- A. Like other rotational quantities, the direction of torque is at right angles to the plane containing the actual rotation.
- B. Understanding torque helps one appreciate the many skills that go into dancing.
 1. Gravity exerts a downward force on a dancer, concentrated at the center of gravity. Unless the center of gravity is directly above the point of contact with the floor, that force will result in a torque that topples the dancer.
 2. A solo dancer's feet provide the only place where forces may be exerted. Producing significant torque, especially *en pointe*, is particularly difficult.

- C. Understanding the relation between torque and angular momentum helps explain some seemingly unintuitive phenomena associated with rotational motion. Remember that Newton's second law says that the direction of the force acting on an object is the direction of the *change* in the object's motion. Similarly, the direction of the torque on an object is the direction of the *change* in its angular momentum.
 1. First consider a vertical object that isn't rotating, so it has no angular momentum. Like the dancer, if it's out of balance, there will be a torque that tends to topple it. While toppling, it is rotating about the point where it contacts the ground. Thus, it gains angular momentum. The change in its angular momentum is, indeed, in the same direction as the torque.
 2. Next, consider what happens if the object is rotating. Now it has angular momentum, whose direction is along its rotation axis. If it is out of balance, there's still a torque, just as before, and that torque causes a change in angular momentum that's in the direction of the torque. But now the change adds to the existing angular momentum—and the effect is to change the direction of that angular momentum. The rotation axis moves—in fact, it traces out a circle. This is the phenomenon of *precession*.
 3. Precession isn't just about toy gyroscopes. It happens when any rotating object is subject to a torque. Our spinning Earth experiences a torque from the Sun's gravity, associated with the slight equatorial bulging of the planet. This results in Earth's rotation axis precessing once every 26,000 years. As a result, the star Polaris will not always be the North Star!
 4. Precession even occurs on the subatomic scale. Subatomic particles, such as protons and electrons, possess an intrinsic angular momentum, called *spin*. Because they're electrically charged, this spin causes them to act like tiny magnets (recall Lecture Fifteen). An external magnetic field exerts a torque that tries to align the particles with the field. But because they're spinning, the particles precess rather than aligning. Precise measurement of the precession rate of protons in a strong magnetic field forms the basis of magnetic resonance imaging (MRI); more on this in Lecture Thirty-Five.
 5. Finally, precession helps explain a common activity from everyday life—bicycling. What keeps a bicycle from falling over? If it's slightly off balance, there's a torque that would cause a stationary cycle to fall over. If the bicycle tilts to the left, that torque points toward the back of the bike, so the angular momentum of the bike's wheels must also change in the backward direction. That can be done by turning the wheel slightly to the left. This, instinctively, is what the rider does—and it's also what happens automatically, because of the torque, when one is riding using no hands! A

moving bicycle is very stable because it is self-correcting—all the result of angular momentum and torque.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapter 8.

W. Thomas Griffith, *The Physics of Everyday Phenomena: A Conceptual Introduction*, chapter 8.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapters 12–13.

Questions to Consider:

1. When an ice skater spins rapidly by drawing in her arms, does a torque act to increase her spin rate? Does her angular momentum increase?
2. You can distinguish a raw egg from a hard-boiled one by rolling each down an incline, starting from rest. Which reaches the bottom first? Why?

Lecture Thirty-Three

The Light Fantastic

Scope: The laser is among the most important inventions of the 20th century. Superficially, the laser's extraordinary intensity and sharply defined beam are what distinguish it from other light sources, but the distinction is actually much deeper. Unlike other light sources, lasers exploit a remarkable form of cooperation among atoms, a cooperation mediated by light itself. The result is a light beam that is, most importantly, coherent—meaning that the light waves emitted by individual atoms are all precisely in step. This coherence is ultimately responsible for laser light's more obvious properties, including sharp beams, high intensity, and purity of color. A wide range of substances—gases, liquids, and solids—can be made to produce laser light. Laser applications range from the obvious and everyday, such as bar-code scanners and laser pointers; to less obvious but still everyday applications, such as sending email and computer data over the optical fibers of the Internet; to industrial applications, such as welding or cutting steel; medical uses, including laser surgery, cancer treatment, and diagnostic microscopy; surveying, ranging, and construction applications; and a host of others. Laser technology is indispensable in the modern world.

Outline

- I. Light is most commonly produced when electrons in atoms jump from higher to lower energy levels. Light or other forms of electromagnetic radiation can also be emitted by jumps among energy levels in molecules, in atomic nuclei, or in semiconductors (recall Lecture Nineteen).
 - A. In a typical light source, such as an ordinary lightbulb, a heated object (the lightbulb's filament) gives off light. This occurs because atoms in the hot object jostle violently against each other, exciting atomic electrons to higher energy levels. Very quickly, the excited electrons jump back to lower energy states, giving up their excess energy in a burst of light. This process is called *spontaneous emission*, and it happens at random in a heated object, with light emitted in all directions. Light from the Sun arises in essentially the same way as in a lightbulb.
 - B. In fluorescent lights and neon signs, an electric current excites atomic electrons in a rarefied gas. Again, the electrons drop to lower energy levels, emitting light in the process. Because the gas is rarefied, the atoms don't interact and a spectrum of discrete colors is emitted, with wavelengths related to the energy difference between the two levels. But again, the process is spontaneous; there is no relation among the bursts of light emitted by different atoms.

- C. Spontaneous emission is not the only reason an atomic electron will drop to a lower energy level. In 1917, Albert Einstein recognized that an electron at a higher energy level could be stimulated to drop to a lower level by the passing nearby of light that had been emitted earlier by the dropping of an electron in a similar atom. This *stimulated emission* is the basis of laser operation.

II. Laser stands for Light Amplification by Stimulated Emission of Radiation.

- A. The key to laser action is to prepare a large number of atoms with electrons in excited states. Normally, most atomic electrons are in the lowest possible energy state, but in a laser, that situation is reversed; therefore, the situation is called a *population inversion*. The atoms can be excited by light, by an electric current, by chemical reactions, or other means.
- B. The first working laser, built in 1960, used a ruby rod surrounded by a flash lamp similar to a camera flash. Light from the flash excited atoms in the ruby, providing the population inversion. Today's lasers use solids, liquids, or gases as the excited medium.
- C. To make a laser, the substance with excited atoms is surrounded by two perfectly parallel mirrors, one of which is not quite perfectly reflecting. When an excited atom drops to its lower energy state, it emits a burst of light. Passing another excited atom, the first burst stimulates a second identical burst—identical in phase (its wave crests align with those of the first burst) and the direction in which it's going. Some light is lost out the sides of the device, but light that happens to be traveling perpendicular to the mirrors gets reflected back and forth, making more and more stimulated emission and building up a significant light intensity between the mirrors. A tiny fraction of this light escapes through the imperfect mirror to make up the laser beam. The beam is remarkably coherent, with waves remaining in step over distances of typically 20 centimeters (about 8 inches), or about half a million wave cycles.
- D. Lasers can also make use of excited states in molecules or in semiconductors. Semiconductor lasers, also called *diode lasers*, are now very inexpensive and widely used. A semiconductor laser consists of a junction between P- and N-type semiconductors (recall Lectures Nineteen and Twenty), with highly polished edges that act like mirrors. An electric current flowing through the device creates electron-hole pairs, which recombine at the junction, emitting light. The emitted light stimulates additional stimulated electron-hole recombination, resulting in laser action. The color or wavelength of the light is determined by the semiconductor's energy band gap (recall Lecture Nineteen).
- E. Lasers are available with power outputs from less than a milliwatt (1/1000 of a watt) to millions of watts. The highest power lasers

produce very short bursts of light with peak power as high as 1,000 trillion watts.

- F. Lasers are available with "light" wavelength or color across most of the electromagnetic spectrum, from microwaves to ultraviolet. Infrared and visible-light lasers are most common. Some lasers are tunable, with output wavelength variable over a wide output range. X-ray and gamma-ray lasers are under development. Very high power x-ray laser action has been achieved using nuclear explosions as the energy source or pump.

III. Today, lasers have almost unlimited uses in consumer products, commerce, industry, and science. Here is just a sample from those many uses:

- A. In communications, diode lasers incorporated into integrated circuits convert electrical signals into light for transmission along optical fibers. Most computer networks are based on such optical communication; so are many land-line telephone systems.
- B. Lasers are at the heart of optical information storage systems, including CDs and DVDs (Lecture Two). Low-power lasers "read" the information on discs, and higher power lasers "burn" discs to store information (Lecture Two). The development of higher energy band-gap semiconductors enabled the higher information capacity of DVD, and progress continues with the new "blu-ray" discs and blue lasers that read them.
- C. Lasers "read" the bar codes at retail and grocery store checkout counters, on library books, on airline tickets, and on shipping and tracking labels.
- D. Lasers with power outputs in the kilowatt (1,000 watts) range make precise cuts in steel and other metals and can weld metals together. Laser cutting tools can be programmed to cut arbitrary shapes, saving manufacturers the cost of developing custom tools for new product models. Lower power lasers (around 100 watts) are used for engraving, shaping "laser cut" keys, and similar applications. In a related application, lasers are used to harden metallic surfaces, resulting in longer wearing parts for machinery, cutting tools, and other uses.
- E. Laser beams can destroy biological tissue, allowing precision laser surgery. Laser beams can be guided through optical fibers deep into body cavities, making laser "knives" less invasive than conventional surgery. Laser vision correction uses this process to reshape the cornea (Lecture Four). Laser beams can also "weld" detached retinas to the correct position at the back of the eye. More on these topics in the next lecture.
- F. Precise, high-speed steering of laser beams by optical or mechanical means allows laser beams to form or reproduce images. Applications

include laser printers and digital copiers, huge (26-foot!) television screens, and laser light shows.

- G. Lasers are widely used in pollution analysis and other applications requiring remote sensing of the environment. Tunable lasers (variable color, wavelength) can be set to the precise wavelength that a particular substance absorbs. By observing scattered light, the type and amount of different contaminants may be determined. This technique may prove useful in detecting minute quantities of materials escaping from clandestine nuclear weapons construction, thereby helping to slow nuclear proliferation.
- H. Laser beams can trap tiny objects, making possible “optical tweezers” that manipulate microscopic structures in individual cells.
- I. Timing of reflected laser pulses provides precise distance and speed measurements. Terrestrial uses include everyday surveying, assembly-line positioning, missile guidance, and law-enforcement applications, such as an automated system for catching red-light runners. In space, lasers track satellites to provide precise position and orbit measurements. Laser beams sent from Earth to reflectors left on the Moon by Apollo astronauts provide measurements of the Moon’s position to better than an inch and help verify Einstein’s general theory of relativity.
- J. The straightness of laser beams makes them useful for leveling, alignment, squaring, and similar procedures in construction and manufacturing.
- K. Very brief laser pulses (trillionths of a second or shorter) are used as high-speed flashbulbs to “freeze” steps in complex biochemical reactions. Much of what we know about the details of such reactions comes from this technique.
- L. In physics research, lasers provide a means of cooling to very low temperatures (millionths of a degree above absolute zero). A laser beam is tuned to the precise wavelength that can be absorbed by atoms in thermal motion. When an atom moving toward the laser absorbs light, the atom slows. The effect on a group of atoms is to lower the temperature.
- M. Coherence of laser beams makes wave interference easy to detect with laser light. Interference-based instruments allow precise measurement of distances with accuracies of a fraction of the wavelength of light (less than a millionth of a meter). Such devices range from industrial instruments that accurately measure the deposition of materials in semiconductor manufacture to a proposed space-based system beaming lasers around a triangle 3 million miles on a side and intended to detect elusive waves of gravity.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, pp. 597–601.

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, pp. 546–550.

Marshall Brain, *Marshall Brain’s How Stuff Works*, pp. 83–84.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, pp. 1125–1127.

Theodore Maiman, *The Laser Odyssey*.

Charles H. Townes, *How the Laser Happened: Adventures of a Scientist*.

Questions to Consider:

1. A laser pointer has a power of only 5/1000 of a watt. Yet its spot on the wall is brighter than the illumination provided by a 100-watt lightbulb or even a 500-watt spotlight. Why?
2. What is a population inversion, and why is it critical to laser operation?
3. Name the most recent encounter you’ve had with laser technology.

Lecture Thirty-Four

Nuclear Matters

Scope: Nuclear physics was born around the turn of the 20th century and matured in mid-century. Today, nuclear physics is inextricably part of our lives in ways both obvious and subtle. In the United States, some 20 percent of our electrical energy is from nuclear sources; although the United States produces the greatest total amount of nuclear energy, the percent reliance on nuclear power is much higher in many other industrialized countries. The continuing spread of nuclear weapons threatens the stability and safety of the planet. At the same time, nuclear applications from medicine to smoke detectors to airline security enhance our safety and well-being. And nuclear technologies help advance knowledge in fields as varied as biology and archeology.

Outline

- I. A brief nuclear history.
 - A. The first hints of nuclear physics came in the late 19th century, with Henri Becquerel's accidental discovery (1896) that uranium compounds fogged his photographic plates. Marie Curie followed with a doctoral thesis on the phenomenon, which she named *radioactivity*. Curie and her husband, Pierre, shared the 1903 Nobel Prize in Physics for their pioneering work, and Marie Curie was later awarded the Nobel Prize in Chemistry for her discovery of two new radioactive elements.
 - B. Physicists soon recognized three types of radiation from radioactive materials, which were eventually identified as electrons (beta radiation), helium nuclei (alpha radiation), and a high-energy form of electromagnetic waves (gamma radiation).
 - C. In 1909–1911, Ernest Rutherford and his collaborators Hans Geiger and Ernest Marsden used alpha radiation from a radioactive source as a probe to explore the nature of the atom. To their surprise, they found that the atom is mostly empty space, with a tiny but massive center carrying positive electric charge. They had discovered the atomic nucleus.
 - D. By the 1930s, physicists understood that the nucleus consisted of two distinct particles: positively charged *protons* and electrically neutral *neutrons*. Because like charges repel, there must be some other force besides electricity that holds the nucleus together. That new force is the *nuclear force*. It's the balance between the nuclear and electrical forces that determines the stability of the nucleus—and explains why larger nuclei tend to be unstable and undergo radioactive decay.
 1. The number of protons in a nucleus—called the *atomic number*—determines how an atom interacts chemically and, thus, what element it belongs to. That's because a neutral atom consists of the nucleus and a number of negative electrons equal to the number of protons in the nucleus, and it is the electrons that determine the atom's chemical behavior.
 2. Atoms of the same chemical element can have different numbers of protons in their nuclei. Such different *isotopes* have identical chemical properties, but they differ in mass and sometimes in other physical properties.
 - E. In 1934, Irène Curie (Marie's daughter) and her husband, Frédéric Joliot-Curie, were the first to produce new radioactive elements by bombarding substances with radiation from natural radioactive substances. (This work won them the Nobel Prize.)
 - F. Soon physicists and chemists were using neutrons as probes of matter, producing new isotopes when the neutrons were absorbed and the bombarded nuclei subsequently underwent nuclear reactions. The Italian physicist Enrico Fermi was a pioneer in this work.
 - G. In 1938, the German chemists Hahn and Strassmann bombarded uranium with neutrons. To their surprise, they found radioactive isotopes of much lighter elements among the products of their experiments. The Austrian-born physicist Lise Meitner, who had fled to Sweden to escape Hitler, soon realized what had happen: Uranium nuclei had split, with an enormous release of energy. Meitner, publishing with her nephew Otto Frisch, coined the term *nuclear fission* to describe this new phenomenon.
 - H. Only the isotope uranium-235, which constitutes just under 1 percent of natural uranium, readily undergoes fission. But when U-235 fissions, it releases several neutrons, typically two or three. Each of these can cause additional fission in nearby uranium nuclei. The result is a *nuclear chain reaction*.
 - I. In the late 1930s, the military implications of nuclear fission and chain reactions were obvious. The rush was on to harness the new energy source. (There's a lot of history crammed into that sentence!) By 1942, a group led by Enrico Fermi had established the first controlled chain reaction, in a reactor built under the stands of the University of Chicago's stadium. Three years later, the first nuclear weapons were detonated, and the nuclear age had begun.
- II. Nuclear fission provides one of two basic ways to extract energy from the nucleus. Fission works because the energy associated with a pair of middleweight nuclei is less than that of a large nucleus, such as uranium; thus, energy can be released by splitting large nuclei. But energy can also be released by joining light nuclei in the process called *fusion*. The famous

curve of binding energy expresses both these possibilities and is at the essence of the possibilities and dangers we face in the nuclear age. The energy released in these nuclear reactions is some 10 million times that released in such chemical reactions as burning coal or metabolizing food.

A. To get sustained energy release from fission, we need to ensure that at least one of the neutrons released in each fission event triggers an additional fission. Neutrons can be lost by escaping from the material or being absorbed by materials other than uranium-235. For this reason, fission requires a certain *critical mass* of uranium.

1. The explosive, rapidly multiplying fission of a nuclear weapon requires uranium highly enriched in the isotope U-235. That's why enrichment technology is crucial in the effort to slow nuclear weapons proliferation. A grapefruit-size sphere of U-235 is enough to make a weapon that can destroy a city.

2. For controlled fission, we want exactly one neutron from each fission event to cause another fission—so we have to lose some of the two or three neutrons released in each fission event. Fuel for a typical fission reactor is only slightly enriched in U-235; as a result, many neutrons hit U-238 (where they make some of the byproducts of fission, especially plutonium). Others are lost to special neutron-absorbing control rods that can be moved in and out of the uranium to control the reaction rate. And because fission occurs more readily with slower neutrons, most reactors include a *moderator*, which slows down the neutrons.

3. There are a number of reactor designs in use around the world, employing different fuel-enrichment levels, different moderators, and different coolants to carry off the heat generated by fission. Each has engineering, economic, and safety advantages and disadvantages. In the United States, nearly all power reactors use ordinary water as the moderator and coolant simultaneously. In some, the water boils directly in the reactor to produce steam that turns a turbine; in others, pressurized water transfers its heat to a secondary water/steam system.

B. Nuclear fusion is much more difficult to achieve, because the electrical repulsion of two positively charged nuclei makes it difficult to get them together. There's no chain reaction involved; just individual fusion events that release energy.

1. Fusion is what powers the Sun and, hence, nearly all life on Earth. The Sun's immense gravity is able to contain the hot, fusing hydrogen at its core. The fusion process in stars ultimately creates the elements we're made of (more on this in the last lecture).

2. Uncontrolled fusion powers thermonuclear or "hydrogen" bombs, the reaction initiated by a fission explosion and a sophisticated focusing of the fission energy on hydrogen fuel.

3. We haven't yet achieved controlled fusion on Earth, although scientists are inching toward that goal. Efforts involve either containing hot (100-million-degree!) gas with magnetic fields or using intense laser beams to produce fusion temperatures and densities in tiny fuel pellets. If fusion succeeds, we will have enough deuterium fuel in the oceans to last 300 billion years! That's 20 times longer than the Sun is going to continue shining. (Deuterium comprises about 1 in every 6,000 hydrogen atoms.)

III. Radiation is a big worry with nuclear technologies. Radiation is harmful, but it's also useful in many ways.

A. Nuclei with too many protons or too many neutrons are unstable and decay by emitting high-energy particles. That's the radiation. More massive nuclei need more neutrons to hold them together; thus, when uranium fissions, the resulting nuclei have too many neutrons and are highly radioactive. Uranium itself is only mildly radioactive.

B. Radioactive nuclei are characterized by their *half-life*, or the time it takes half the nuclei in a given sample to decay. Half-lives range from fractions of seconds to billions of years.

C. Radiation is harmful to biological systems because it damages DNA and other biomolecules. This can cause cell death, genetic mutations, or cancer. About 80 percent of the radiation we receive is from natural sources, including 11 percent from radioactive potassium in our own bodies. The remaining 20 percent is largely from medical procedures; nuclear power is responsible for less than 1 percent.

D. Nuclear radiation has a great many practical applications that affect our lives. Here are just a few:

1. Radiocarbon dating has vastly expanded our knowledge of the past, providing accurate ages for once-living objects up to about 50,000 years old. (Other radioisotope dating methods go back through the billions of years of geologic time.) Cosmic rays interact with Earth's atmosphere to produce the radioactive isotope carbon-14, with a 5,730-year half-life. The radioactive carbon forms carbon dioxide, which is taken up by plants, then animals. As a result, living things maintain a steady level of C-14. When they die, uptake ceases, and the level drops as the C-14 decays. Measuring C-14 levels in a long-dead sample of wood, bone, or other formerly living material determines its age.

2. Smoke detectors save thousands of lives each year in the United States. The simplest, most common, most effective, and most economical smoke detector is the ionization detector. This type of detector contains a tiny quantity of the radioactive isotope americium-241 (half-life 432 years), which emits alpha particles (helium nuclei) as it undergoes radioactive decay. The alpha

particles collide with air molecules, giving them an electric charge and making the air an electrical conductor. An electric current is passed through the air, and the detector monitors this current. If smoke particles enter the detector, they absorb the alpha particles and reduce the current, which triggers the alarm.

Americium has 95 protons in its nucleus and, like other elements with more protons than uranium's 92, does not occur in nature. Americium is formed in nuclear reactors by a sequence of nuclear reactions that begin when uranium-238 captures a neutron. Our source of this valuable substance is, thus, the waste from nuclear power plants.

Speaking of fire safety, you don't need to worry about the exit signs in a public building going out in the event of a power failure. Some of these signs are powered by the radioactive hydrogen isotope tritium (hydrogen-3; half-life 12.3 years). They're similar to ordinary fluorescent lamps, in which electrons strike a phosphor coating to produce light, except that the electrons come not from electric current but from the radioactive decay of tritium.

3. Long used for chemical analysis, the process of *neutron activation* exposes unknown materials to neutrons, which are absorbed and make the materials radioactive with short half-lives. The characteristic energies of the subsequent radioactive decay provide unique "fingerprints," giving the elemental composition of the material. Neutron activation is under development as one of the most promising and reliable methods for scanning airline luggage to detect explosives and other dangerous substances.

Suggested Reading:

Paul Hewitt, *Conceptual Physics*, chapters 33–34.

Richard Wolfson, *Nuclear Choices: A Citizen's Guide to Nuclear Technology*.

Going Deeper:

Richard Wolfson and Jay M. Pasachoff, *Physics for Scientists and Engineers*, chapters 43–44.

Richard Garwin and Georges Charpak, *Megawatts and Megatons: A Turning Point in the Nuclear Age?*

Questions to Consider:

1. In the outline above, while discussing the history of the nuclear age around the start of World War II, I noted, "There's a lot of history crammed into that sentence!" Explore that history, and in particular, determine what roles Albert Einstein played (and what he didn't do) to advance the nuclear age.

2. A typical coal-burning power plant is fueled many times a week with 110-car trainloads of coal. A typical nuclear plant of the same power-generating capacity typically gets a couple of truckloads of uranium once every year or so. Why the difference? What number in the outline above speaks to this difference?

Lecture Thirty-Five

Physics in Your Body

Scope: Although physics is ultimately behind all aspects of the human body, it's often more insightful to describe the body's workings in terms of biochemistry, physiology, neurobiology, and related fields. However, some aspects of the body are best described in terms of physics. Electric circuit concepts play a major role in the nervous system and the heart. Simple ideas from mechanics show how the muscles and skeleton act to permit movement. Principles of fluid dynamics govern blood flow. And the passage of nutrients into our cells, and the excretion of waste from the cells, is often described in terms of an electric circuit. Perhaps even more significantly, physics and physics-derived technologies provide unprecedented and minimally invasive techniques for imaging the interiors of our bodies. Finally, physics-based techniques allow the precise delivery of energy used in curing diseases, especially cancer.

Outline

- I. Principles of physics govern the workings of our bodies. Although biology and related fields provide a more insightful overview, many individual aspects of our bodies can be understood in terms of physics.
 - A. Concepts of Newtonian mechanics describe our bodies' overall motion or lack of motion. Examples include balance and center of gravity, tension and compression forces in muscles, and principles we instinctively apply to minimize forces on our bodies and avoid injury. The forces exerted on and by our bodies can be surprisingly large.
 - B. Our nerves provide the communications link between body and brain, brain and body. Specialized cells called *neurons* actually transmit the signals. The neurons have extensions called *axons*, up to several feet long, that act very much like electrical cables. Our understanding of axons comes from analysis of electric currents and voltages, both by measurement and by modeling the axon as an electric circuit. Similar circuit analogies apply to cells in general and describe the flow of nutrients and waste in and out of the cell in terms of electric currents.
 - C. The heart is particularly amenable to electrical analysis.
 1. The heart muscle consists of elongated cells that, in their resting state, have positive electric charge on the outside and negative charge on the inside. Because charge is distributed evenly all around, the cell is not electrically charged, and there's no uneven distribution of electric charge (recall Lecture Thirteen).
 2. When the heart beats, the cells temporarily lose their electric charge. They do so in a "wave" that sweeps from the top of the heart to the bottom. While they're losing charge, the cells have a slightly more negative charge on the upper end and slightly more positive on the lower end. This pattern results in electrical voltage differences that can be measured on the skin. Electrocardiography machines measure this voltage as it varies with time, and physicians use the result to diagnose heart conditions.
 3. Special cells comprise a *pacemaker* that sets the rhythm of the heartbeat. If this natural pacemaker fails, an artificial pacemaker is implanted in the chest; it works by stimulating the heart with an electrical signal. Sometimes the heart goes into a rapid, shallow, and fatally ineffectual beating called *fibrillation*. Defibrillators delivering a heavy dose of electric current can restart the normal rhythm—another example of the heart's electrical nature.
 - D. Principles of pressure and fluid flow determine the behavior of our blood. The two numbers associated with blood pressure are the maximum and minimum pressures (in millimeters of mercury that pressure can support) that the beating heart transmits to the blood.
 1. In the common disease arteriosclerosis, fatty plaque builds up in the arteries. Plaque can break loose and clog a smaller artery, resulting in stroke or heart attack.
 2. Physics shows another danger: Plaque narrows the artery, meaning that blood must flow faster past the plaque than it does in the unobstructed part of the artery. But by Bernoulli's principle (Lecture Ten, on airplane flight), that means the pressure in the artery drops. If this drop is too great, the artery can collapse and cut off blood flow.
- II. Physics-based technology provides a myriad of new ways to image the body's interior, many of them noninvasive.
 - A. X-rays, a form of electromagnetic radiation (Lecture Eighteen), penetrate soft tissue but not bone. Captured on film, x-rays thus provide diagnostic information about teeth, bone, or foreign objects in the body. Use of x-ray-opaque substances, such as barium, allows imaging of soft tissue, such as the intestine or stomach.
 1. The German physicist Wilhelm Roentgen accidentally discovered x-rays in November of 1895. In studying the new rays, he quickly found they could form an image of the bones in his hand. By December, he showed a physical-medical society an x-ray image of his wife's hand, and a mere month later, x-rays were hailed as a medical miracle.
 2. Modern x-ray techniques can be almost as simple as Roentgen's, but more sophisticated applications have been developed. Computerized axial tomography (CT or CAT scan) takes a series

of x-ray images from many points on a circle surrounding the patient; a computer then reconstructs a three-dimensional picture from the individual two-dimensional images.

B. *Magnetic resonance imaging (MRI)* is a much newer and very versatile imaging technique. Unlike x-rays, there is no hazardous radiation, nor is it necessary to introduce any foreign substance into the body. MRI is noninvasive. And MRI, again in contrast to x-rays, does an excellent job of imaging soft tissue.

1. The principle behind MRI is called *nuclear magnetic resonance (NMR)*; the term *nuclear* was scrupulously avoided in naming the medical technique). NMR uses a very strong magnetic field (tens of thousands of times stronger than Earth's magnetic field), usually from a superconducting electromagnet (Lectures Fourteen and Fifteen). Atomic nuclei (in particular, protons or hydrogen nuclei) act as tiny magnets and tend to align with such a strong field. But their intrinsic spin (a quantum-physics property that can be thought of, roughly, as an actual rotation) causes them to precess about the magnetic field the way a top or gyroscope precesses in the presence of gravity (Lecture Thirty-Two). They can precess either aligned parallel (spin up) or antiparallel to the field (spin down). Under normal conditions, the numbers are nearly equal, but a few more are aligned with the field. However, providing energy in the form of radio waves of just the right frequency (photon energy) causes nuclei to flip antiparallel (spin down). When they flip back up, they emit a radio signal. Detecting this signal locates the precessing protons and tells about their magnetic environment. Used this way, NMR is a powerful tool for determining molecular structure.
2. Medical imaging generally uses nuclear magnetic resonance of the single protons that constitute the nuclei of hydrogen. Hydrogen is especially abundant in fat and water, both common in the body, so hydrogen nuclei are everywhere. In an MRI apparatus, the strong magnetic field is inside a cylinder that can accommodate the entire body. The signal from the flipping protons becomes a measure of the number of protons. The magnetic field varies slightly with position, and only those at just the right location can absorb radio waves of the appropriate frequency. That way, the location of the flipping protons can be determined. The strength of the signal from each position is then a measure of the density of protons or, very nearly, the density of tissue. A computer organizes the data from all regions under examination to produce images of the body's interior.
3. MRI is not only a diagnostic tool for disease but is widely used in physiological and neurophysiological studies, especially of brain function.

C. Diagnostic techniques of *nuclear medicine* use radioactive substances to image body structures and processes.

1. Radioactive versions of chemicals that concentrate in particular tissues can be used to image those tissues. Radioactive phosphate is absorbed selectively in bone; to make a bone scan, the substance is injected into the bloodstream, then makes its way into the bones. Radiation detectors outside the body then form an image of the bones. Similarly, radioactive iodine settles in the thyroid gland and can be used to diagnose thyroid problems. Radioactive thallium effectively images the brain and its blood-flow patterns.
2. A particularly sophisticated nuclear imaging technique is *positron emission tomography (PET)*. Positrons are the antimatter opposite of electrons, and they're emitted in the decay of some radioactive substances (see *The Teaching Company's Einstein's Relativity and the Quantum Revolution* for more on antimatter). Positrons emitted in body tissue soon meet electrons and annihilate, sending out two gamma rays (a very high energy form of electromagnetic radiation) of precise energy and in opposite directions. Arrays of detectors pick up the gamma rays, and a computer reconstructs the points where they were emitted, forming an image of the radioactive substance. Many of the radioactive substances used in PET are short lived and, thus, very safe (some must even be made right in the hospital, using particle accelerators). PET can be used to study dynamic processes, such as breathing, blood oxygen uptake, blood flow, and even brain processes used in thinking.

III. Physics also plays a role in curing disease.

- A.** Lasers (Lecture Thirty-Three) replace scalpels as precision tools for surgery. One common example is laser vision correction (Lecture Four). Optical fibers can guide surgical laser beams deep into body cavities, and laser surgery is particularly effective at minimizing post-surgical bleeding. In *laser angioplasty*, a catheter tipped with a high-intensity ultraviolet laser is threaded into the arteries. Short bursts of laser radiation vaporize plaque, clearing congested arteries.
- B.** Strong sound waves (shock waves) can be used to break up kidney stones, allowing them to pass without resort to surgery. This can be done either with sound-emitting probes inserted near the stones or externally with sound penetrating through the skin. Some blood-clot-destroying drugs are much more effective if clots are irradiated with ultrasound while being supplied with drugs.
- C.** Both electric currents and ultrasound stimulate bone growth and are used to help heal broken bones in particularly difficult cases or where natural healing takes a very long time.

D. One of the most significant physics-based medical treatments is radiation therapy to kill or shrink tumors. High-energy radiation, either in the form of particles or electromagnetic energy (x-rays and gamma rays) kills cells by stripping electrons off atoms and changing the physical and chemical structure of molecules, particularly DNA. Cells may be killed outright or they may fail to divide. Radiation is now used in roughly half of all cancer cases, either to cure the disease or to enhance the chance of cure using other treatments.

1. Radiation is particularly effective against rapidly dividing cells. That's why radiation exposure is especially dangerous for children, but it's also one reason why radiation selectively kills cancer cells. Cancer cells are also less organized, and that makes them less able to repair cell damage.
2. Early radiation therapy used external beams of gamma rays from highly radioactive materials. With these beams, both position and penetration depth were difficult to control.
3. Much modern radiation therapy uses high-energy beams generated in particle accelerators that are miniature versions of the machines used in high-energy physics. Aiming beams from different directions allows energy to be concentrated at the disease site while minimizing damage to healthy tissue the beams pass through. Beams consist of either electromagnetic radiation (x-rays or gamma rays) or particles of matter. Electrons are often used because they're light and easy to accelerate, but in the past decade, proton beams have come into widespread use. The heavier protons have the advantage that they deliver most of their energy at the disease site, minimizing damage to surrounding tissue.
4. Additional ways to deliver radiation therapy include radioactive materials attached to the skin; radioactive "seeds" implanted directly into a tumor site; or radioactive solutions ingested or injected, which then make their way to a particular site.

Suggested Reading:

Louis A. Bloomfield, *How Things Work: The Physics of Everyday Life*, chapter 19, section 1.

Paul Hewitt, *Conceptual Physics*, chapter 33.

Going Deeper:

Bettyann Kevles, *Naked to the Bone: Medical Imaging in the Twentieth Century*.

Howard Sochurek, *Medicine's New Vision*.

Paul Davidovits, *Physics in Biology and Medicine*.

Steven Vogel, *Life's Devices: The Physical World of Animals and Plants*.

Questions to Consider:

1. The operation of airbags in a car is similar to the considerations in this lecture about bending one's knees when landing a jump. What's the similarity?
2. Proton beams penetrate the body more deeply than electron beams of the same energy. Why?

Lecture Thirty-Six

Your Place in the Universe

Scope: You are the product of an evolutionary sequence that began with the simplest possible states of matter and energy and proceeded through ever increasing complexity to the point where at least one agglomeration of matter—the human brain—became conscious and able to contemplate the Universe around it. A remarkable set of subtle circumstances allowed the Universe to evolve the chemical elements that proved necessary for life as we know it. In the early stages of cosmic evolution, only the simplest elements—hydrogen and helium—were produced in significant quantities. All the other elements, common and uncommon, up to and including those as heavy as iron, were formed in the interiors of long-dead stars. Those stars exploded, spewing their contents into interstellar space. This “stardust” eventually condensed to form new stars and planets. On at least one of those planets, life arose and, eventually, consciousness. Our everyday lives are, thus, intimately connected with the lives of the stars and with the earliest instants of time.

Outline

- I. Your place in the Universe is planet Earth, a rare chunk of solid matter that is much cooler than the visible matter of the Universe but much warmer than the overall average temperature. Yours is the place where the Universe began—but so is every other place. Your place in time is some 14 billion years since the Universe began. You’re connected to cosmic history through the matter of which you’re made.
- II. A brief history of the Universe shows an evolutionary sequence beginning with the simplest forms of matter and energy and evolving through ever more complex structures, including some 14 billion years after the beginning, the conscious brain. The dominant theme in this evolution is the expansion of the Universe and the concomitant cooling—a process that lowers the average energy and allows more complex structures to coalesce and persist. Our detailed understanding of this cosmic history depends on many disparate observations, but the overall picture comes from three distinct discoveries.
 - A. In the early 20th century, the Universe was believed to be essentially static. Individual stars and planets might come and go, but the overall structure had always been the same and always would be. So ingrained was this belief that it led Albert Einstein to commit what he called “my greatest blunder.” Einstein’s 1916 general theory of relativity suggested that the Universe should not be static but expanding or contracting.

Einstein introduced a “fudge factor” called the *cosmological constant* to provide a kind of “antigravity” that would maintain a static Universe against the mutual gravitational attraction of all its components.

- B. In the 1920s, the astronomer Edwin Hubble (for whom the space telescope is named) made a series of observations that showed the light from distant galaxies to be reddened, with the degree of reddening increasing with distance.
 1. Hubble used the then-new 100-inch telescope at Mount Wilson outside Pasadena, California. Before the advent of this telescope, there was controversy about the very existence of other galaxies. Today, we know the galaxies as vast agglomerations of stars and other matter, containing typically tens to hundreds of billions of stars.
 2. Hubble interpreted the reddening of the distant galaxies’ light as a Doppler shift (recall Lecture Six). Because reddening represents a lengthening of light’s wavelength, Hubble concluded that galaxies were moving away from us with speeds proportional to their distances. Hubble’s discovery suggested that the Universe is expanding, with galaxies rushing away from each other in the aftermath of a cosmic explosion—the *Big Bang*—that began a finite time ago. Although it might seem like Earth is at the center of this expansion, it isn’t. There is no center or, equivalently, every point has equal claim to be the “center.”
- C. The idea of an evolving Universe remained controversial through the mid-20th century. An alternative, the *steady-state* theory, suggested that matter was continually created to fill the void left by the receding galaxies. That way, the large-scale structure of the Universe would remain unchanged. But then a 1965 discovery gave overwhelming evidence for a Universe beginning with a Big Bang. In that year, two Bell Laboratories scientists, Arno Penzias and Robert Wilson, were trying to find the source of some “noise” (static) in a radio antenna. They found that the noise came from outside their antenna and seemed independent of where the antenna was pointed. Coincidentally, theorists at nearby Princeton University predicted that a Universe starting in a Big Bang should, today, be pervaded by microwave radiation with just the characteristics being measured at Bell Labs. Penzias and Wilson had discovered the *cosmic microwave background radiation (CMB)*. Today, the CMB provides some of the most precise and detailed information we have about the early Universe. More on this topic shortly. (Penzias and Wilson shared the Nobel Prize for their discovery.)
- D. Through the 1970s and 1980s, both theorists and experimentalists working with large particle accelerators made advances in our understanding of elementary particle physics. (Much more on this in

Professor Pollock's Teaching Company course *Particle Physics for Non-Physicists*). These new understandings were then applied to explore the interactions of matter and energy in the very early Universe and to predict the formation of simple structures, such as nuclei and atoms. Today, particle physics, which deals with the smallest objects in the Universe, and cosmology, which deals with the largest scales, are inextricably linked.

- III. The timeline for cosmic evolution starts a mere 10^{-43} of a second—that's 1 over 1 followed by 43 zeroes—after the beginning. We can't go back further than that because our present understanding of physical reality does not cover conditions that prevailed before that time. To do so would require a merging of quantum physics with general relativity, and that has yet to be achieved.
- A. At the earliest times we can know, the Universe was an almost structureless soup of matter and energy. Only the most basic of particles could exist, and the temperature was far too high for them to stick together. Creation of matter from energy and annihilation of matter into energy occurred routinely. Although this description has been on good theoretical footing for some time, experiments in the early 2000s at Brookhaven National Laboratory have momentarily reproduced matter under conditions that existed before even a millionth of a second had passed.
 - B. Around a millionth of a second out, the temperature had dropped to the point that quarks could join to form the familiar protons and neutrons that we know from nuclear physics. But these particles still couldn't stick together.
 - C. By about 3 minutes, the temperature had finally dropped to the point where protons and neutrons could join to make atomic nuclei. For roughly the next half hour, protons and neutrons joined to make helium nuclei (2 protons, 2 neutrons) and trace amounts of a few other simple nuclei, notably deuterium (hydrogen-2; 1 proton, 1 neutron; recall Lecture Thirty-Four). At the end of the first half-hour, the temperature and density were too low for further *nucleosynthesis*, and the process stopped. Theoretical calculations show that the matter of the Universe at that time should have been about 25 percent helium, 75 percent hydrogen (bare protons). When we observe the Universe at large today, we indeed find that it consists of about 25 percent helium and 75 percent hydrogen. The rest—including the elements we're made of—is a tiny deviation from this hydrogen-helium Universe. And virtually none of the elements beyond hydrogen and helium were formed in that first half-hour.
 - D. At about 300,000 years, the temperature had dropped to the point where electrons could join nuclei to form neutral atoms. Before this, the

Universe had been opaque, because free charged particles readily absorb light (a form of electromagnetic radiation; recall Lecture Eighteen). But at 300,000 years, the Universe suddenly became transparent because it now consisted largely of neutral atoms. The electromagnetic radiation emitted as electrons "fell" into orbit around the nuclei was therefore free to travel throughout the Universe with little chance that it would be stopped by matter. That radiation would become the CMB.

- 1. As the Universe continued to expand and cool, the wavelength of the radiation itself lengthened, until today, it is predominantly microwave radiation. The distribution of the radiation is characteristic of the average temperature of the Universe, about 2.7 kelvins, or 2.7 degrees Celsius above absolute zero (recall Lecture Twenty-Five).
 - 2. Satellites designed explicitly to study the CMB have confirmed that it is remarkably uniform, with essentially the same intensity and temperature in all directions. But there are tiny fluctuations, and they tell us a great deal about the structure of the early Universe. In particular, the fluctuations indicate a "lumpiness" that represents the "seeds" of the large-scale structure—galaxies and clusters of galaxies—that characterize the Universe today. And detailed analysis of the sizes of the CMB fluctuations gives evidence for a period of exceptionally rapid expansion that occurred around 10^{-32} second.
 - 3. You, too, can observe this "fossil" radiation from the beginning of the Universe. Tune your TV to a channel where there's no signal in your area, and you'll see "snow" on the screen. About 1 percent of the energy being captured by your TV to make this snow is the CMB!
- E. When the Universe was a few hundred million years old, the slight "lumpiness" evident at the time the CMB formed led to gravitational "clumping" of matter to form galaxies. With new instruments mounted on the Hubble Space Telescope, we can see distant galaxies as they were a mere 400 million years after the beginning and, thus, begin to understand how galaxies form and evolve and how they're distributed in the Universe.
 - F. For the first roughly 9 billion years, the Universe continued to expand at an ever slower rate, as the mutual gravitational attraction pulled at the receding galaxies. But about 5 billion years ago, the expansion began to accelerate. This phenomenon, discovered only in 1998, shows the existence of a mysterious force, called *dark energy*, that effectively counters gravity. Understanding dark energy is an ongoing goal of contemporary cosmology.
- IV. New observations of the early 2000s show that the first stars also formed

just a few hundred million years after the beginning, perhaps in a burst of extravagant star birth. Since then, the stars have continually recycled and processed the material of the Universe, building up a mixture richer in elements heavier than the primordial hydrogen and helium.

- A. Stars form as gas and dust agglomerate under the influence of their mutual gravity. Regions dense in gas and dust constitute “stellar nurseries” with prolific star formation.
- B. As more matter accumulates in the nascent star, the pressure and temperature at the center increase. Eventually, the temperature becomes high enough for hydrogen nuclei to begin fusing together (recall Lecture Thirty-Four). The immense gravity of the stellar material confines the fusing gas, and the star settles into a long period of steady “nuclear burning.”
 - 1. How long a star burns its nuclear fuel depends on its mass. The Sun has a lifetime of about 10 billion years; 5 have already passed. But a star with 30 times the Sun’s mass only lives about 10 million years.
 - 2. A star begins with a series of nuclear reactions that ultimately convert hydrogen (a single proton) into helium-4 (2 protons, 2 neutrons). In more massive stars, three helium nuclei can fuse to make carbon. Actually, two first fuse to make an unstable isotope of beryllium. By a wonderful fluke of nature, the beryllium lasts just long enough that a third helium nucleus can join to make carbon. If that did not happen, there would be no heavier elements and no life!
 - 3. As a massive star exhausts the hydrogen at its core, it collapses and heats up. Then helium “burning” begins. Once helium is exhausted, carbon “burning” commences, producing a myriad of different nuclei—most commonly oxygen and silicon, which just happen to be the most abundant elements on Earth. The process of collapse, heating, and new nuclear reactions continues through the production of iron, the most stable nucleus (recall Lecture Thirty-Four and the curve of binding energy). Near the end of its life, a massive star has an onion-like structure with layers of different elements formed in the various fusion processes. The abundance of the various elements in the Universe is established by these nuclear processes.
 - 4. Unlike our Sun, which will end its life rather calmly, a massive star ends in a violent *supernova* explosion that spews the star’s contents into interstellar space. Eventually, the material is recycled into new stars, and the process repeats—each time enriching the Universe with heavier elements. (Elements heavier than iron don’t form in the stars but in the brief moments of the supernova explosions themselves.)

- C. When new stars condense from the interstellar medium, they may form stellar systems, with less massive planets in orbit around a central star. The first extrasolar planet was discovered in 1995, and today we know dozens of planetary systems. Our solar system, which formed some 5 billion years ago, is not unique.
 - 1. Less massive planets have weaker gravity and cannot hold onto such light elements as hydrogen and helium. Thus, they develop into solid bodies rich in such elements as oxygen, silicon, carbon, and iron.
 - 2. At a range of distances from the central star is the *habitable zone*, where a planet with the requisite size and composition would have an environment conducive to the origin and evolution of life. In our solar system, that zone encompasses Venus, Earth, and Mars, but at present, only Earth has conditions conducive to life.
 - 3. Sometime around the first billion years of Earth’s existence, life arose. Soon, photosynthesis by blue-green algae began changing Earth’s atmosphere, introducing a significant level of oxygen.
 - 4. Roughly a billion years ago, multicellular organisms evolved.
 - 5. Some 400 million years ago, life began to colonize the land.
 - 6. Sixty-five million years ago, an asteroid collided with Earth, wiping out the dinosaurs and paving the way for mammals.
 - 7. Somewhere around 4 million years ago, the first humans evolved, with a consciousness that let them understand and appreciate the Universe and, eventually, its long history. That is our place in the Universe today: literally, descendants of the stars and the nuclear processes that forged the elements that today make our bodies, brains, and ultimately, our consciousness.
- V. What of the future? In a paper entitled “Time without End: Physics and Biology in an Open Universe,” physicist Freeman Dyson argues that, once established, consciousness can exist into the infinite future of an ever-expanding Universe. Recent studies, especially the 1998 discovery of accelerated expansion, somewhat temper Dyson’s optimistic assessment. But it remains a grand vision of physics in our lives and our lives as part of the ongoing physics of the whole Universe!

This course has been about physics—mostly practical, everyday physics. Yet physics touches all other aspects of our lives; for this reason, I end, fittingly, with literature: selected passages from Pattiann Rogers’s poem “The Origin of Order.”

Suggested Reading:

Sky and Telescope, October 2003, special issue, “The New Cosmology.”

Lawrence Krauss, *Atom: An Odyssey from the Big Bang to Life on Earth...and Beyond*.

Going Deeper:

Eric Chaisson, *Cosmic Evolution: The Rise of Complexity in Nature*.

Alan Guth, *The Inflationary Universe*.

James B. Kaler, *Cosmic Clouds : Birth, Death, and Recycling in the Galaxy*.

Questions to Consider:

1. In what sense is the CMB radiation a “fossil” from an earlier time in the history of the Universe?
2. Trace your own lineage back to the core of a long-dead, massive star.

Glossary

Aerodynamic lift: The upward force of air on an airplane or bird wing.

Ampere: The unit of electric current, equal to 1 coulomb of charge per second.

Amplifier: An electronic circuit that boosts either the voltage or current of an electrical signal.

Amplitude: The size of the disturbance that constitutes a wave.

AND: The logical operation whose output is 1 only if both inputs are 1.

Angular momentum: A measure of an object’s rotational motion; the product of rotational inertia and angular velocity.

Angular velocity: A measure of the rotation rate of a rotating object.

Antenna: A system of electrical conductors used to send or receive electromagnetic waves.

Apparent weight: The “weight” read by a spring scale, which may or may not be your actual weight (the force that gravity exerts on you), depending on whether or not you’re accelerating.

Apparent weightlessness: The condition encountered in any freely falling reference frame, such as an orbiting spacecraft, in which all objects have the same acceleration and, thus, seem weightless relative to their local environment.

Arteriosclerosis: A buildup of fatty plaque in the walls of arteries. Can lead to blockage or to collapse, as described by Bernoulli’s principle.

Atomic number: The total number of protons in an atom’s nucleus and, hence, the number of electrons in a neutral atom. Determines what element an atom belongs to.

Axons: Long extensions of neurons that carry signals to other neurons.

Battery: A device that converts chemical energy to electrical energy by separating positive and negative charge.

Beats: Sound heard at the frequency difference between two sound waves of very similar but not identical frequency.

Bernoulli’s principle: A statement of energy conservation in a fluid, showing that the pressure is lowest where the flow speed is greatest and vice versa.

Big Bang: The explosive event that began the Universe as we know it.

Bit: A single binary digit, which can have only one of the two values 0 or 1.

Buoyancy force: The upward force on an object that is less dense than the surrounding fluid, resulting from greater pressure at the bottom of the object.

Byte: A sequence of 8 bits.

Cache: Special high-speed computer memory used for temporary storage of data and instructions.

Carnot engine: A simple engine that extracts energy from a hot medium and produces useful work. Its efficiency, which is less than 100 percent, is the highest possible for any heat engine.

CCD: See **charge-coupled device**.

Center of mass: A point where an object acts as though all its mass were concentrated.

Central processing unit (CPU): The main electronic circuitry of a computer, which performs fundamental operations on digital data.

Centrifugal force: There's no such thing! Banish this word from your vocabulary. See Lecture Nine.

Centripetal force: Any real, physical force that acts to keep an object moving in a circular path. Examples include gravity for the Moon and the friction of tires on the road for a car rounding a curve.

Charge-coupled device (CCD): A light detector that captures visual information using electrons in individual picture elements (pixels). Used in digital cameras and many other devices.

Chip: See **integrated circuit**.

Circular orbit: One of many possible paths for an orbiting object; in a circular orbit, the object remains at a fixed distance from the gravitating center and its speed remains constant.

Classical physics: The theories and descriptions of physical reality developed before about the year 1900, specifically excluding relativity and quantum physics.

Clock: A circuit inside a computer that generates a periodic signal used for synchronizing and timing all computer operations.

Cogeneration: The process of generating both usable thermal energy and electrical energy in the same power plant.

Collision: An intense interaction between objects that lasts a short time and involves very large forces.

Compression: A technique used to reduce the number of bits needed to store digital information.

Conduction: Heat transfer by physical contact.

Conductor: A material that contains electric charges that are free to move and can, thus, carry electric current.

Conservation-of-energy principle: The principle that energy cannot be created or destroyed, strictly valid in pre-relativity physics.

Conserved quantity: A quantity whose value does not change, at least in a given circumstance.

Constructive interference: See **interference**.

Convection: Heat transfer resulting from fluid motion.

Convection oven: An oven that uses forced circulation of hot air to reduce cooking time.

Cosmic microwave background: Electromagnetic radiation in the microwave region of the spectrum, which pervades the Universe and represents a "fossil" relic of the time when atoms first formed, about half a million years after the Big Bang.

Cosmological constant: A quantity first introduced by Einstein into his equations of general relativity to provide a kind of antigravity effect that would keep the Universe static; later discredited. Recently revived as a possible explanation for the 1998 discovery that the expansion of the Universe is accelerating.

Coulomb: The unit of electric charge.

CPU: See **central processing unit**.

Critical mass: The mass of fissile material (uranium, plutonium) needed for a self-sustaining nuclear chain reaction.

Curve of binding energy: A graph describing the energy release possible in forming atomic nuclei; shows that both fusion of light nuclei and fission of heavy nuclei can release energy.

Data bus: Channel for high-speed data transfer among different components of a computer.

Depletion region: The region surrounding a PN junction, in which there is a dearth of free charges.

Destructive interference: See **interference**.

Differential GPS: Use of two Global Positioning System receivers to reduce timing and atmospheric errors.

Diffraction: The phenomenon whereby waves change direction as they go around objects.

Diffraction limit: A fundamental limitation posed by the wave nature of light, whereby it is impossible to image an object whose size is smaller than the wavelength of the light being used to observe it.

Diffuse reflection: The reflection of waves, especially light, from a rough surface. The light is scattered at different angles and does not form an image.

Diffusion: The process where a material or type of particle moves from regions of higher concentration to regions of lower concentration.

Digital information storage: The encoding and storage of information as a sequence of digital 0s and 1s.

Diode: An electronic device using a PN junction to restrict the flow of electric current to one direction only.

Doped semiconductor: A semiconductor to which impurities have been added to alter the material's electrical conductivity.

Doppler effect: The increase in perceived frequency (higher pitch for sound, bluer color for light) of waves when the source approaches the observer. Also, the decrease in frequency when the source recedes from the observer.

Drag: The backward-pointing aerodynamic force that resists the forward motion of an airplane, bird, or other heavier-than-air flying object.

Dynamic memory: Memory that stores information as electric charge. Must be refreshed several thousand times per second.

Elastic collision: A collision in which energy is conserved.

Electric charge: A fundamental property of matter that determines electric and magnetic interactions.

Electric current: A net flow of electric charge.

Electric field: The influence that surrounds an electric charge, resulting in forces on other charges.

Electric generator: A device that uses electromagnetic induction to convert mechanical energy to electrical energy. Typically, a generator involves a coil of wire rotating in a magnetic field.

Electromagnet: A magnet made by passing electric current through a coil of wire.

Electromagnetic induction: A fundamental phenomenon wherein a changing magnetic field produces an electric field.

Electromagnetic spectrum: The range of electromagnetic waves, organized by frequency or wavelength.

Electromagnetic wave: A structure consisting of electric and magnetic fields, each produced from the change in the other, that propagates through space carrying energy. Light is an electromagnetic wave. In vacuum, all electromagnetic waves travel at exactly the speed of light.

Electromagnetism: The branch of physics dealing with electricity and magnetism, described by Maxwell's equations as developed in the mid-19th century.

Electromechanical relay: A device using an electromagnetically actuated switch to allow one electric circuit to control another.

Electrostatic precipitator: A device that uses electric fields to remove particulate matter from smokestacks.

Energy: One of the two basic "things" that makes up the Universe. Energy is what makes everything happen.

Energy gap: The range of unavailable energies that separates two bands of allowed energy levels in a semiconductor.

Entropy: A measure of disorder. The second law of thermodynamics states that the entropy of a closed system can never decrease.

Equatorial orbit: An orbit that remains above Earth's equator.

Exclusive OR: The logical operation whose output is 1 if either, but not both, of its inputs is 1.

Extrinsic semiconductor: See **doped semiconductor**.

Faraday's law: The mathematical statement describing electromagnetic induction.

FET: See **field-effect transistor**.

Field-effect transistor (FET): A transistor in which an electric field exercises the control function.

First law of thermodynamics: The statement that energy is conserved, expanded to include thermal energy.

Flip-flop: An electronic circuit that has only two possible states. Used as the fundamental unit in static semiconductor memory.

Fluid friction: A friction-like force that slows the flow of a fluid, especially near a solid boundary.

Free fall: The state of motion of an object on which the only force acting is gravity. The object need not be moving downward!

Frequency: The number of complete wave cycles per unit of time; inverse of the wave period.

Friction: A force that acts between two surfaces, opposing any relative motion between them.

Fuel cell: A device that combines two chemicals (typically, hydrogen and oxygen), producing electric current in the process.

Fusion: A nuclear reaction in which light nuclei join to produce a heavier nucleus, releasing energy in the process.

Gate: The controlling electrode of a field-effect transistor; an unrelated definition is a circuit that performs a basic logic function.

General relativity: Einstein's 1915 theory that describes gravity as the curvature of spacetime.

Geosynchronous orbit: An equatorial orbit at an altitude of about 22,000 miles, where the orbital period is 24 hours. A satellite in such an orbit remains fixed over a point on the equator.

Gigabyte: A measure of computer memory, equal to about a billion bytes (exact value 2^{30} , or 1,073,741,824 bytes).

Gravitational lensing: The bending of light by the gravity of massive astrophysical objects.

Gravity: A universal attractive force that acts between all objects in the Universe.

Greenhouse effect: The trapping of outgoing infrared radiation by certain atmospheric gases, resulting in the warming of a planet.

Greenhouse gas: A gas that absorbs infrared radiation, thus contributing to the greenhouse effect.

Ground-fault interrupter: A safety device that senses imbalance in current on two wires, then shuts off the circuit to prevent electric shock.

Gyroscope: A rapidly spinning object whose rotation axis tends to maintain a fixed orientation.

Habitable zone: The region around a star where conditions are appropriate for life as we know it.

Half-life: The time it takes for half of the atoms in a sample of radioactive material to decay.

Heat capacity: A measure of the energy required to change an object's temperature.

Heat pump: A refrigerator run in reverse, pumping heat from the cooler outdoor environment into a building.

Hole: A place in a semiconductor where an electron is missing from the crystal structure. Acts as a positive charge.

Holographic image: A three-dimensional image made by recording interference patterns of wave fronts coming from the object being imaged.

Hyperfine transition: A transition between two very closely spaced atomic energy levels.

Induced electric field: An electric field produced not by electric charge but by a changing magnetic field.

Insulator: A material with no or few free electric charges and, thus, a poor carrier of electric current.

Integrated circuit: A circuit built on a single piece of silicon.

Interference: The process whereby two waves, occupying the same place at the same time, simply add to produce a composite disturbance. Interference may be constructive, in which the two waves reinforce to produce an enhanced composite wave, or destructive, in which case the composite wave is diminished.

Internal energy: The energy associated with random molecular motion; commonly but mistakenly called "heat."

Intrinsic semiconductor: A semiconductor made from a pure material.

Ion: An atom that has lost or gained an electron, thus possessing an electric charge.

Ionosphere: A region of Earth's atmosphere, beginning about 50 miles up, that contains free electrons and is, therefore, electrically conductive; affects the timing of GPS signals.

Kinetic energy: The energy associated with an object's motion.

Lagrangian point, L1: A point roughly 1 million miles sunward of Earth, where a spacecraft's orbital period is 1 year, allowing it to stay on the line between Earth and Sun.

Laser: A device that produces light or other electromagnetic radiation through stimulated emission; stands for *Light Amplification by Stimulated Emission of Radiation*.

Laser angioplasty: The use of laser beams to clear clogged arteries by vaporizing plaque.

Latent heat: Energy associated with a substance's being in a state requiring higher energy, as in the latent heat of water vapor, which can be released when the water condenses.

Law of inertia: The statement that a body in motion (or at rest) remains in uniform motion (or at rest) unless a force acts on it.

LCD: See **liquid-crystal display**.

LED: See **light-emitting diode**.

Lens: A piece of transparent material shaped so that refraction brings light rays to a focus.

Lift: See **aerodynamic lift**.

Light-emitting diode (LED): A diode engineered to produce visible or near-visible light when current flows across its PN junction.

Liquid-crystal display (LCD): A visual display device that uses electric fields to reorient the molecules of a liquid crystal, thereby altering the polarization of light.

Low-Earth orbit: An orbit whose altitude above Earth's surface is a small fraction of Earth's radius. The period of low-Earth orbits is about 90 minutes.

Magnetic field: The influence surrounding a moving electric charge (and, thus, a magnet) that results in forces on other moving charges (and on magnets or magnetic materials).

Magnetic resonance imaging (MRI): A procedure that uses spinning protons in a magnetic field to form images of the body's interior.

Magnetron: A special vacuum tube in which electrons undergo circular motion, producing microwaves.

Maxwell's equations: A set of four equations that describe all electromagnetic phenomena of classical physics.

Mechanics: The study of motion.

Megabyte: A measure of computer memory, equal to about a million bytes (exact value 2^{20} , or 1,048,576 bytes).

Memory: An electronic circuit that maintains a given state until the state is explicitly changed.

Metal-oxide-semiconductor field-effect transistor (MOSFET): A type of transistor widely used in computer circuits.

Microprocessor: The single-chip CPU of personal and other small computers.

Minority charge carriers: The free charges that are in a minority in a given semiconductor (electrons in P type, holes in N type).

Mirage: An image formed by refraction because of temperature gradients in the air.

Moderator: In a nuclear reactor, a substance that slows neutrons to make them more effective at causing fission.

Modern physics: The theories and descriptions of physical reality developed after about the year 1900, including specifically, relativity and quantum physics.

Momentum: A quantity that describes the "amount of motion" in a moving object, accounting for both velocity and mass.

Moore's law: The statement that the number of transistors per integrated circuit grows exponentially, doubling every year or two. Moore's law has held since the 1960s.

MOSFET: See **metal-oxide-semiconductor field-effect transistor**.

Motherboard: A circuit board holding the CPU, memory, and other components central to the operation of a computer.

MRI: See **magnetic resonance imaging**.

NAND: NOT AND; the logical operation whose output is the opposite of AND.

Natural greenhouse effect: The effect of natural greenhouse gases, particularly water vapor and carbon dioxide, in raising Earth's temperature some 60° F above what it would otherwise be.

Negative charge: The type of electric charge on the electron.

Net force: The sum of all forces acting on an object.

Neurons: Specialized cells that transmit electrochemical signals in the brain and nervous system.

Neutral buoyancy: The state of neither rising nor sinking that occurs for an object of the same density as the surrounding fluid.

Neutron: An electrically neutral component of the atomic nucleus.

Neutron activation: A process of inducing artificial radioactivity by bombarding substances with neutrons; the subsequent radioactive decay is used to identify the substances.

Newton's first law of motion: This is the same as the law of inertia.

Newton's second law of motion: The statement that an object's acceleration is proportional to the net force applied to it and inversely proportional to its mass.

Newton's third law of motion: The statement that forces always come in pairs; if one object exerts a force on a second object, the second exerts an equal but opposite force back on the first.

Nonthermal energy transfer: Energy transfer that does not rely on a temperature difference, as in a microwave oven.

Nonvolatile memory: Memory that retains information even when the power is off, as in a digital camera.

NOR: NOT OR; the logical operation whose output is the opposite of OR.

NOT: The logical operation whose output is the opposite of its input.

N-type semiconductor: A semiconductor doped so that the dominant free charges are negative electrons.

Nuclear chain reaction: An ongoing reaction in which neutrons released in nuclear fission go on to cause additional fission events.

Nuclear force: The force that binds protons and neutrons to form atomic nuclei.

Nuclear magnetic resonance (NMR): The process at the heart of MRI, whereby protons absorb radio waves of just the right frequency to set them precessing in a magnetic field.

Nuclear medicine: The use of radioactive substances to image body structures and analyze physiological processes.

Nucleosynthesis: The process of forming atomic nuclei, especially in stars and in the early Universe.

Ohm's law: The statement, valid for some materials, that the electric current is proportional to the applied voltage and inversely proportional to the material's resistance.

Optical storage medium: A medium, such as the CD or DVD, that encodes information in ways that can be read using light.

Optics: The branch of physics dealing with light and its behavior.

OR: The logical operation whose output is 1 if either or both inputs are 1.

Pacemaker: A specialized group of cells that provides the signal to govern the rhythmic beating of the heart.

Parallel communications: Data transfer that moves many bits simultaneously on separate wires.

Period: The time interval between two successive wave crests; equivalently, the time for a complete wave cycle.

PET: See **positron emission tomography**.

Phase change: A change in a material, as from solid to liquid or liquid to gas, that occurs abruptly at certain values of temperature and pressure.

Phase diagram: A diagram showing how the phases of a substance relate to its temperature and pressure.

Photolithography: A process using light to lay down patterns for forming integrated circuits.

Photovoltaic cell: A semiconductor device that converts light directly into electrical energy.

Piezoelectric device: A device using a material that generates electricity when squeezed or distorted; conversely, the device changes size or shape when a voltage is applied to it.

Pixel: An individual element of a digital image.

Plasma: An ionized gas, sometimes called the "fourth state of matter."

PN junction: A junction of P- and N-type semiconductors, with the property that electric current can flow in only one direction.

Polar orbit: An orbit that passes over Earth's poles. As Earth rotates, a satellite in polar orbit passes over every point on the planet.

Polarization: The direction of an electromagnetic wave's electric field.

Population inversion: A situation in which more higher level atomic states are populated than are lower level states. Needed for laser action.

Positive charge: The type of electric charge on the proton.

Positron emission tomography (PET): A medical imaging technique using gamma rays from the annihilation of positrons (anti-electrons) released in the decay of radioactive substances.

Potential energy: Stored energy associated with a configuration of objects.

Power: The rate of producing or expending energy. In electrical devices, power is the product of voltage and current.

Precession: The gradual change in direction of a rotating object's rotation axis as a result of an applied torque.

Proton: A positively charged component of the atomic nucleus.

P-type semiconductor: A semiconductor doped so that the dominant free charges are positive holes.

Pulsar: A rapidly spinning neutron star.

Quantum computing: Computing based on the states of quantum-mechanical systems.

Quantum physics: The theory, developed in the early 20th century, that describes physical reality at the atomic scale and below. In this realm, the discrete, "quantized" nature of both matter and energy become important.

Radiation: Heat transfer by electromagnetic waves.

RAM: See **random-access memory**.

Random-access memory (RAM): Memory whose individual storage locations can all be accessed in equal time, as opposed to sequential memory, such as that on magnetic tape.

Read-only memory (ROM): Memory whose state cannot be changed.

Rechargeable battery: A battery in which the passage of electric current from an outside source results in the storage of chemical energy.

Reflection: The phenomenon whereby a wave strikes a material and rebounds at the same angle with which it struck the material.

Refraction: The phenomenon of waves changing direction of propagation when going from one medium to another.

Resistance: The property of a material that describes how it impedes the flow of electric current.

Resistor: A device formulated to have a specific electrical resistance.

Reverse bias: The condition in which a voltage is applied across a PN junction, with positive to the N-type side. Results in very little electric current.

ROM: See **read-only memory**.

Rotational inertia: A measure of an object's resistance to change in rotational motion.

Second law of thermodynamics: A general principle stating that systems tend to evolve from more ordered to less ordered states.

Semiconductor: A material that lies between insulators and conductors in its capacity to carry electric current. The electrical properties of semiconductors are readily manipulated to make the myriad devices at the heart of modern electronics.

Semiconductor memory: Memory made with transistors and other devices. The fastest memory used in computers.

Serial communications: Data transfer that moves one bit at a time, using a single wire.

Shock wave: A very strong, abrupt wave produced when a wave source moves through a medium at a speed faster than the waves in that medium. An example is a sonic boom from a supersonic airplane.

Sliding friction: The frictional force between two surfaces in relative motion; smaller than static friction.

Special relativity: Einstein's 1905 theory that shows how all uniformly moving frames of reference are equivalent as far as the laws of physics are concerned. Requires modification of our commonsense notions of time and space.

Specular reflection: Reflection off a smooth surface that appears shiny and produces an image, as in a mirror.

Spontaneous emission: The emission of light or other electromagnetic energy as an electron jumps spontaneously from a higher energy level to a lower one.

Standing waves: Waves that "stand" without propagating on a medium of fixed size. The vibrations of a violin string are standing waves.

Static electricity: Electricity associated with stationary distributions of electric charge.

Static friction: The frictional force between two surfaces at rest relative to each other.

Static memory (SRAM): Semiconductor memory in which information is stored in the states of flip-flops.

Steady-state theory: The idea, now widely discredited, that the overall structure of the Universe never changes.

Stimulated emission: The emission of light or other electromagnetic energy as an electron jumps from a higher energy level to a lower one, stimulated to do so by the nearby passage of similar electromagnetic energy.

Sublime: To change directly from solid to vapor, without going through the liquid state.

Superconductor: A material that, at sufficiently low temperature, exhibits zero resistance to the flow of electric current.

Superheated: A liquid above its boiling point but nevertheless not boiling.

Supernova: The violent explosion marking the endpoint of massive stars.

Temperature: A measure of the average thermal energy.

Terminal speed: The maximum speed reached by a falling object, which occurs when air resistance becomes equal in magnitude to the force of gravity.

Theory of Everything: An as-yet-undeveloped theory that would describe all of physical reality.

Thermal energy: See **internal energy**.

Thermal energy balance: A state wherein energy leaving a system is balanced by incoming energy.

Thermal pollution: Waste heat dumped to the environment, usually associated with the thermodynamic inefficiency of power plants.

Thermistor: A temperature-measuring device utilizing the property that the resistance of an intrinsic semiconductor decreases with increasing temperature.

Thermocouple: A device that uses the thermoelectric effect to measure temperature.

Thermodynamics: The branch of physics dealing with heat and related phenomena.

Thermoelectric effect: The production of a voltage at a junction of two dissimilar materials when heated.

Toner: The small particles that take the place of ink in dry copying and laser printing (xerography).

Torque: The rotational analog of force; torque depends on force and where that force is applied.

Total internal reflection: Complete reflection that occurs as light attempts to go from a more dense to a less dense medium, as from water to air.

Transformer: A device that uses electromagnetic induction to transform high-voltage/low-current electricity to low-voltage/high-current and vice versa.

Transistor: A semiconductor device with three separate electrical connections, in which current or voltage in one circuit controls current or voltage in another circuit. The basic control element in both digital and analog electronics.

Truth table: A table that displays all possible states of a logic gate.

Volatile memory: Memory that stores information only as long as power is applied.

Voltage: A measure of the energy per unit of electric charge.

Watt: A unit of power, equal to 1 joule of energy per second.

Wave: A traveling disturbance that carries energy but not matter.

Wavelength: The distance between two successive wave crests.

Weight: The force that gravity exerts on an object.

Word: A sequence of binary bits, usually 32 or 64 bits, on which a computer performs operations.

Working fluid: A substance used in refrigerators and engines to transfer heat; often undergoes phase changes in the process.

XOR: See **exclusive OR**.

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