



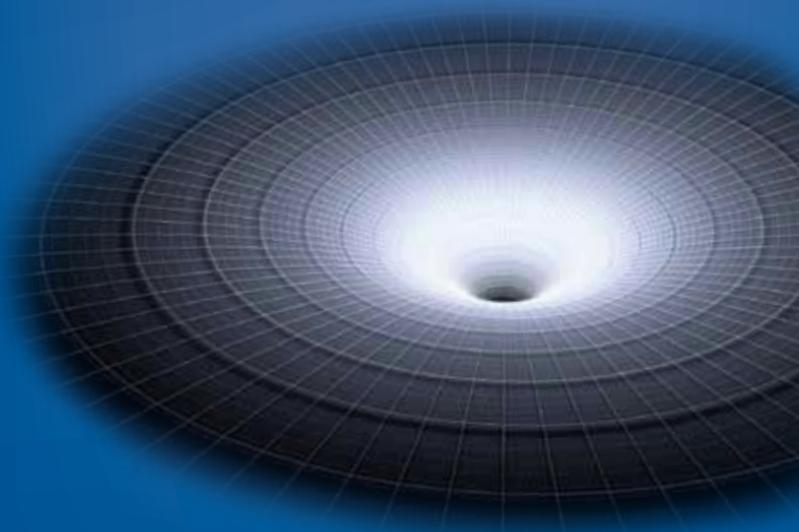
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Physics

Einstein's Relativity and the Quantum Revolution: Modern Physics for Non-Scientists, 2nd Edition

Course Guidebook

Professor Richard Wolfson
Middlebury College



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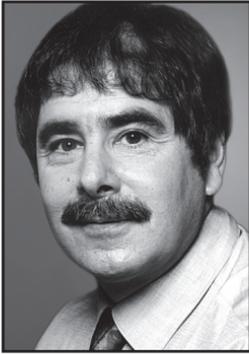
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Professor Richard Wolfson is Professor of Physics at Middlebury College, where he has also held the George Adams Ellis Chair in the Liberal Arts. He did undergraduate work at MIT and Swarthmore College, graduating from Swarthmore with a double major 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 College. His published research includes such diverse fields as medical physics, plasma physics, solar energy engineering, electronic circuit design, observational astronomy, and theoretical astrophysics. Professor Wolfson's 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. As a college professor, Wolfson is particularly interested in making physics relevant 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 foreign languages. Wolfson is also an interpreter of science for nonscientists; he has published in *Scientific American* and wrote *Nuclear Choices: A Citizen's Guide to Nuclear Technology* (MIT Press, 1993). The original version of this course on physics was produced in 1995, and in 1996, Wolfson produced another Teaching Company course, *Energy and Climate: Science for Citizens in the Age of Global Warming*. Although he has been at Middlebury for his entire post-Ph.D. career, 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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Einstein's Relativity and the Quantum Revolution: Modern Physics for Non-Scientists, 2nd Edition

Scope:

The 20th century brought two revolutionary changes in humankind's understanding of the physical universe in which we live. These revolutions—relativity and the quantum theory—touch the very basis of physical reality, altering our commonsense notions of space and time, cause and effect. The revolutionary nature of these ideas endows them with implications well beyond physics; indeed, philosophical debate continues to this day, especially over the meaning of quantum physics.

Is time travel to the future possible? You bet—but if you don't like what you find, you can't come back! Are there really such bizarre objects as black holes that warp space and time so much that not even light can escape? Almost certainly! And do the even weirder cousins of black holes, wormholes, exist—perhaps affording us shortcuts to remote reaches of space and time? Quite possibly! Is the universe governed by laws that strictly predict exactly what will happen in the future or is it governed by chance? In part, by chance! All these and other equally strange consequences flow from relativity and quantum physics.

Many people think that relativity and quantum physics must be far beyond their comprehension. Indeed, how many times have you heard it said of something difficult that “it would take an Einstein to understand that”? To grasp these new descriptions of physical reality in all their mathematical detail is indeed daunting. But the basic ideas behind relativity and quantum physics are, in fact, simple and comprehensible by anyone; for example, a single, concise English sentence suffices to state Einstein's theory of relativity.

This course presents the fundamental ideas of relativity and quantum physics in 24 lectures intended for interested people who need have no background whatsoever in science or mathematics. Following a brief history of humankind's thinking about physical reality, the lectures outline rigorously

the logic that led inexorably to Einstein's special theory of relativity. After an exploration of the implications of special relativity, we move on to Einstein's general theory of relativity and its interpretation of gravity in terms of the curving of space and time. We see how the Hubble Space Telescope provides some of the most striking confirmations of general relativity, including near-certain confirmation of the existence of black holes. Then we explore quandaries that arose as physicists began probing the heart of matter at the atomic and subatomic scales, quandaries that led even the great physicist Werner Heisenberg to wonder "can nature possibly be as absurd as it seems to us in these atomic experiments?" The resolution of those quandaries is the quantum theory, a vision of physical reality so at odds with our experience that even our language fails to describe the quantum world. After a brief exposition of quantum theory, we explore the "zoo" of particles and forces that, at the most fundamental level, comprise everything, including ourselves. We then bring together our understanding of physical reality at the smallest and largest scales to provide a picture of the origin, evolution, and possible futures of the entire universe and our place in it. Finally, we consider the possibility that physics may produce a "theory of everything," explaining all aspects of the physical universe.

A first version of this course was first produced in 1995. In this new 1999 version, I have chosen to spend more time on the philosophical interpretation of quantum physics and on recent experiments relevant to that interpretation. I have also added a final lecture on the "theory of everything" and its possible implementation through string theory. The graphic presentations for the video version have also been extensively revised and enhanced. But the goal remains the same: to present the key ideas of modern physics in a way that makes them clear to the interested layperson. ■

Time Travel, Tunneling, Tennis, and Tea

Lecture 1

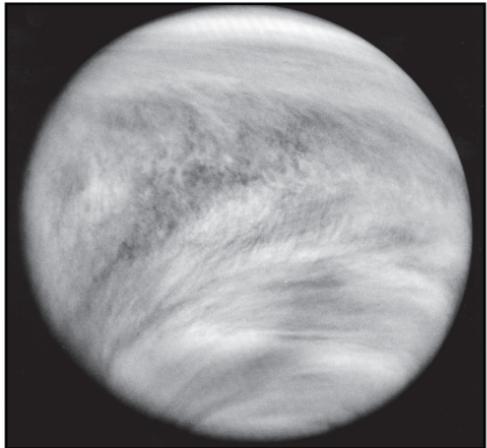
This is a course in the great ideas that shaped the physics of the 20th and 21st centuries. It's not a course in all of physics and it's not a course in the really latest, most contemporary ideas, although we will touch on those. Rather, it's a course in the true, fundamental ideas that set the tone for all the physics that's occurred since the year 1900.

The two big ideas of modern physics are relativity and quantum physics. Relativity radically alters our notions of space and time, while quantum physics reveals a universe governed ultimately not by strict determinism but, in part, by pure chance. Modern physics stands in contrast to classical physics, developed before 1900 but still applicable to everyday phenomena.

Although modern physics forces radical changes in our philosophical thinking about the physical world, its basic ideas are nevertheless accessible to non-scientists.

I'll start with two impossible tales—or are they? The first tale involves time travel, where I'll use a set of twins as an example. The twins start out at the same age. One makes a high-speed round-trip journey to a distant star while the other stays home on Earth. When the traveling

twin returns, they're different ages! The second tale involves tunneling; I'll use a prison as an example. You're trapped in a concrete-walled prison cell. You pace back and forth all day, confined by the walls. Suddenly, you find yourself on the outside! It seems impossible, at least according



NASA/NSSTC/Pioneer Venus Orbiter

Ultraviolet image of Venus's clouds.

to anything your common sense tells you. But it definitely happens with subatomic particles.

Physics is the subject that describes our physical environment, from the smallest subatomic particles to the entire universe. Physics is important to everyone, not just physicists! Classical physics is the realm of physics developed before 1900, which is still applicable to most everyday phenomena (such as driving a car, engineering a skyscraper, designing a telescope, launching a satellite, generating electric power, predicting weather and planetary motion, and so on). Modern physics has been developed in the 20th century and describes phenomena at very small (i.e., atomic) scales or when relative speeds approach that of light. This course is about the two big ideas at the heart of modern physics: relativity and quantum physics.

Physics is the subject that describes our physical environment, from the smallest subatomic particles to the entire universe.

Relativity, developed largely by Einstein beginning in 1905, is a great equalizer. It asserts that everyone experiences the same laws of physics, regardless of their location or state of motion. In this way, relativity builds on the Copernican notion that Earth does not occupy a privileged position in the universe. Despite its simple content, relativity radically bends and blends our notions of time and space.

Quantum physics reveals a noncontinuously dividable, or “grainy,” universe at the smallest scales and with it, bids farewell to strict determinism. In other words, at the fundamental levels of matter, causation is a matter of statistical probabilities, not certainties.

Physics is a human activity, which most scientists nevertheless believe is a quest toward understanding an underlying objective reality. Developing new ideas of physics, especially with fundamentals such as relativity and quantum physics, is often more like a creative artistic process than the stereotypical “scientific method” emphasized in school science courses.

It doesn't take an Einstein to understand modern physics! The goal of this course is to make the key ideas of modern physics accessible, comprehensible, and even simple for the interested non-scientist. For example, you can play tennis, or brew a cup of tea, equally at home, on a cruise ship, on Venus, or on a planet in a distant galaxy. Trivial as this example is, understanding it means grasping and accepting the essential idea of Einstein's relativity, namely, that the laws that govern physical reality are the same everywhere in the universe. ■

Suggested Reading

Hoffmann, *Relativity and Its Roots*, Chapter 1.

Questions to Consider

1. Articulate why it is, in terms of your own understanding of time, that you find the example of the time-traveling twins disturbing.
2. Why do you suppose it is that you don't have to take into account the ship's motion in the example of playing tennis on a cruise ship?

Heaven and Earth, Place and Motion

Lecture 2

In this lecture I've got to take you back ... further to what I'll call pre-classical physics; physics before the time of Isaac Newton because we want to understand how ideas evolve from that physics into classical physics and then set the stage for the several quandaries I mentioned that then led to the introduction of modern physics.

Understanding motion is the key to understanding space and time, because to move is to move through space and time. Is there a “natural” state of motion? The ancients thought so; they thought that there were different “natural states” for terrestrial and celestial motion. Aristotle (c. 349 B.C.) described a geocentric universe with planets and the Sun orbiting Earth in perfect circles. Ptolemy (c. 140 A.D.) added circles-on-circles (“epicycles”) to represent planetary motion more accurately. Terrestrial objects naturally assume a state of rest close to the center of the universe (Earth); force is required to maintain motion.

Copernicus (1543) posited a Sun-centered universe, but maintained the celestial/terrestrial distinction and the idea of perfect circular motion in the celestial realm.

Through careful study of planetary observations collected by Tycho Brahe (1546–1601), Kepler (c. 1610) showed that planetary orbits are ellipses, not circles. He developed mathematical laws describing the orbits, but gave no explanation for why the planets moved as they did.

Galileo (1564–1642) discovered that the Sun was blemished with sunspots, found moons orbiting Jupiter, and observed the phases of Venus. These discoveries helped dispel the notion of celestial perfection and lent support to Copernicus's heliocentric theory.

Galileo discovered that the Sun was blemished with sunspots, found moons orbiting Jupiter, and observed the phases of Venus.

Experimenting with motion on Earth, Galileo concluded that all objects fall with the same acceleration. Through a “thought experiment,” he developed the law of inertia—that an object continues in straight-line motion at constant speed unless disturbed by an outside influence (force). Thus, he redefined the “natural state” of motion as straight-line motion at constant speed. According to Galileo, force is needed for *change* in motion, not for motion itself. ■



Aristotle.

Library of Congress, Prints and Photographs Division,
LC-USZ61-563.

Essential Reading

Hoffmann, *Relativity and Its Roots*, Chapter 2.

Mook and Vargish, *Inside Relativity*, Chapter 1, Sections 1–5.

Suggested Reading

Einstein and Infeld, *The Evolution of Physics*, Chapter 1 through p. 33.

Questions to Consider

1. For the ancients, objects in the heavens moved naturally in circular motion. Would Galileo consider circular motion a “natural state” of motion? Why or why not?
2. Why isn’t Galileo’s conclusion that objects naturally move in straight-line motion at constant speed obvious from our everyday experience? Can you describe an environment in which it would be obvious?

The Clockwork Universe

Lecture 3

Before we get into the mechanism of the clockwork universe, let's look a little bit about the individual whose name is most associated with this idea, Sir Isaac Newton.

Isaac Newton was born in 1642, the year of Galileo's death. Newton developed his famous three laws of motion, quantifying Galileo's earlier idea that uniform, straight-line motion is natural and changes only if outside influences (forces) act. Newton also considered gravity and had the brilliant insight that the same force that pulls an apple to Earth is also what holds the Moon in its orbit—thus, putting to rest the false dichotomy between celestial and terrestrial motion.

Newton developed the concept of *universal gravitation*, suggesting that every object in the universe attracts every other object, with a force that depends on their masses and the distance between them. Together, Newton's laws of motion and gravity showed that the planets must move in Kepler's elliptical orbits and hinted at the possibility of artificial satellites. The predictability inherent in Newton's laws suggests a "clockwork universe" in which all that happens in the universe is completely determined by the initial motions of its constituents. (On a historical note, Newton did some of his most productive work while away from Cambridge to escape the plague. Today, Stephen Hawking occupies Newton's chair at Cambridge.)

Inherent in the ideas of Galileo and Newton is the *Principle of Galilean Relativity*: The laws of motion work exactly the same way for anyone as long as he or she is moving uniformly. In other words, the laws of physics known to Galileo and Newton preclude such statements as "I am moving" or "I am at rest" from having any absolute meaning.

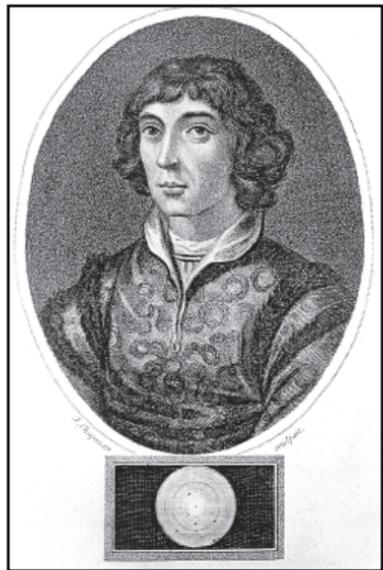
Such statements as "I am moving" or "I am at rest" have no absolute meaning; they are only meaningful when they are about motion or rest relative to something else.

Newton's three laws:

- Newton's first law restates Galileo's discovery that objects move uniformly unless acted on by outside forces.
- Newton's second law, $F = ma$, tells quantitatively how a given force (F) produces changes in motion (acceleration, a) in an object of mass m .
- Newton's third law, "for every action there is an equal and opposite reaction" says that forces always come in pairs; if object A exerts a force on object B, then B exerts a force of equal strength back on A.

Newton's law of gravity:

- The famous story of Newton and the apple may be a myth. But if it is true, its significance lies in Newton's realization that apple and moon are attracted toward Earth by the same force, which Newton named *gravity*.
- Thus, Newton subsumed celestial and terrestrial motion under the same laws. He generalized to the idea of *universal gravitation*: that every object in the universe attracts every other, with a force that depends on their masses and the distance between them.
- Using his law of gravity and his newly invented calculus, Newton proved that the planets must move in elliptical orbits, just as Kepler had observed.



Nicolas Copernicus.

- Newton anticipated artificial satellites, showing that an object, given enough speed, will “fall” around Earth, pulled by gravity out of the straight-line path it would otherwise follow. Today, we are highly dependent on satellites for communications, weather prediction, navigation, science, and other applications.

To review, ideas about motion evolved until, by Newton’s time, all motion in the universe was assumed to be governed by the same deterministic laws.

The Principle of Galilean (Newtonian) Relativity (we might call it the “original principle of relativity”):

- The laws of motion are the same for anyone, provided that he or she is in uniform motion.
- Such statements as “I am moving” or “I am at rest” have no absolute meaning; they are only meaningful when they are about motion or rest *relative* to something else.
- There are many ways to say this! Remember the cruise ship, Venus, and the distant galaxy. There is simply no experiment you can do in, say, a uniformly moving cruise ship, train, plane, or even planet that will answer the question of whether or not you are moving. (You can answer the question “Am I moving relative to Earth, or to my star, or to whatever?”—but that’s a question about *relative* motion, not *absolute* motion.) ■

Essential Reading

Hoffmann, *Relativity and Its Roots*, Chapter 3.

Mook and Vargish, *Inside Relativity*, Chapter 1, Sections 6–8; Chapter 2, Sections 1–5.

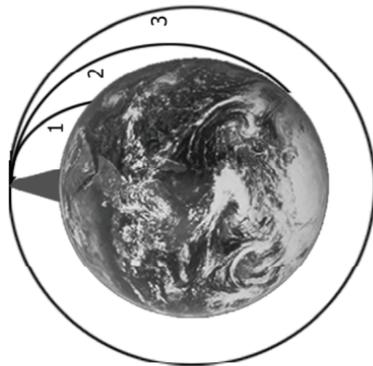
Suggested Reading

Einstein and Infeld, *The Evolution of Physics*, Chapter 1, pp. 34–67.

Questions to Consider

1. Many people think astronauts in an orbiting spacecraft are “weightless” because “there’s no gravity in space.” How is this view inconsistent with Newton’s ideas of gravity and motion?
2. You’re on a plane flying through calm air. You eat, read, and relax just as you would on the ground—you can’t tell that you’re “moving.” Yet when you look out the window, you see the ground slipping backwards. Why can’t you conclude definitely that you and the plane are “moving”? What can you conclude?

Note: Figures explaining key concepts presented in each lecture are placed immediately following each lecture. The graphical part of each figure is the same as the corresponding graphic used in the video version of the course, thus giving audio customers a chance to visualize what Dr. Wolfson is discussing. In addition, each figure contains explanatory text to further reinforce the concept under discussion.



Orbits

Newton's thought experiment describes the motion of an object when thrown off a very tall mountain.

Object 1, thrown with modest force, falls in a curved path toward the earth.

Object 2, thrown with greater force, falls farther than object one, but still eventually falls to earth.

Object 3, thrown with such force that it falls towards the earth at the same rate that the earth is curving away beneath it, describes a circular orbit. Absent air resistance or other mitigating factors, it will continue in this circular motion forever.

Let There Be Light!

Lecture 4

This lecture will be an attempt to give you, in half an hour, what I normally teach in an entire semester, namely, the subject of electricity and magnetism.

The study of motion is not all there is to physics. The ancient Greeks and Chinese knew, respectively, about electricity and magnetism. By the 18th century, scientists engaged in serious experimental studies of electricity and magnetism. The two phenomena turned out to be related; magnetism can produce electrical effects and vice versa.

Early experiments with static electricity showed that electric charge is a fundamental property of matter. Like charges repel; opposites attract. Early experiments with magnets showed that all magnets have two poles. Like poles repel; opposite poles attract.

The *field concept* describes electric and magnetic interactions in terms of invisible *fields* that exert forces on charges and magnets. This view contrasts with the earlier *action-at-a-distance* concept, in which electric charges and magnets somehow “reach out” across empty space to influence other charges or magnets. Experiments led to two laws showing how electric and magnetic fields arise from electric charges and magnets, respectively. The field concept can also be applied to gravitational attraction.

Electricity and magnetism are intimately related; hence, *electromagnetism*. A moving electric charge produces magnetism—a phenomenon at the basis of many technologies, including electric motors. Such a moving electric charge is constituted by the electrons moving in atoms. Changing magnetic fields produce electric fields. This process

Maxwell showed that his equations implied the existence of electromagnetic waves, structures of electric and magnetic fields that travel through empty space.

is an integral part of how computer disks, audio and videotapes, and electric power generators work.

In the 1860s, Scottish physicist James Clerk Maxwell suggested that if magnetic fields produce electric fields, why not the opposite as well? Maxwell incorporated this suggestion into the laws of electromagnetism, completing four equations that describe all electromagnetic phenomena. He showed that his equations implied the existence of *electromagnetic waves*, structures of electric and magnetic fields that travel through empty space.



Marchese Guglielmo Marconi.

Library of Congress, Prints and Photographs Division, LC-USZ62-77563.

He calculated the speed of such waves from quantities appearing in his equations and found it was equal to the known speed of light! Then he concluded that light must be an electromagnetic wave, making optical science a branch of electromagnetism. Other electromagnetic waves now known include radio, infrared, ultraviolet, x-rays, and gamma rays, which differ in their frequencies (and therefore wavelengths).

In 1887, Heinrich Hertz generated and received electromagnetic waves in a laboratory. In 1901, Guglielmo Marconi transmitted radio waves across the Atlantic Ocean. ■

Essential Reading

Hey and Walters, *Einstein's Mirror*, Chapter 2, through p. 29.

Mook and Vargish, *Inside Relativity*, Chapter 2, Section 7.

Suggested Reading

Casper and Noer, *Revolutions in Physics*, Chapter 12.

Einstein and Infeld, *The Evolution of Physics*, Chapter 2, through p. 33.

Questions to Consider

1. Why was Maxwell's assertion that a changing electric field should produce a magnetic field crucial to the existence of electromagnetic waves?
2. Maxwell's realization that the phenomena of optics can be explained by electromagnetism is an example of scientific synthesis, in which hitherto unrelated phenomena are found to be related. What are some other examples of such syntheses?

Maxwell's Equations

And God said...

Equation	What it says...
$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$	How charges attract/repel
$\nabla \cdot \mathbf{B} = 0$	No isolated magnetic poles
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	Changing magnetism produces electricity
$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	Changing electricity produces magnetism

...and there was light.

Speed c Relative to What?

Lecture 5

I want to introduce a new concept. It's a concept called a frame of reference. What's a frame of reference? Well, you'd probably say it's something like your point of view. And in physics it is something like your point of view. It's basically sort of your state of motion; the things that share your state of motion.

I'm going to use that concept of frame of reference a lot in this and subsequent lectures. It's a crucial concept in relativity, because the relativity principle—Galilean or Einsteinian—is fundamentally about frames of reference. But before we delve into the concept of relativity, I want to summarize what we've covered so far.

Between about 1600 to 1750, Galileo, Newton, and others developed a mechanical understanding of physical reality. The mechanical universe is *deterministic*, and a *relativity principle* holds. Between about 1750 to 1900, Maxwell and others developed an understanding of electromagnetic phenomena, including light.

Now we're ready to discuss frames of reference and the validity of physical laws. A frame of reference is the place that shares your motion (if you're in a car, it's the car; if you're in a plane, it's the plane). A simple question: In what frame of reference are the laws of motion (mechanics) valid? Answer: In any frame of reference in uniform motion (the Principle of Galilean Relativity, from Lecture 3).

Another simple question: In what frame of reference are the laws of electromagnetism (Maxwell's equations) valid? An equivalent question is "In what frame of reference does light go at speed c ?" or, put another way, "Relative to *what* does light go at speed c ?" One possibility is that light goes at speed c relative to its source. This is ruled out by astronomical observations, especially of double-star systems.

The 19th-century answer was that light goes at speed c relative to the *ether*, a hypothetical medium, or substance, believed to permeate the entire universe. The ether was thought to be the medium through which electromagnetic waves propagate, just as sound waves propagate through air and water waves through water. Ether must have some unusual properties, being at once very stiff to account for the high speed of light, yet letting planets and other moving objects slip through without resistance and being able to permeate the tiniest of spaces. But to 19th-century physicists, ether's existence seemed essential.

One branch of physics, mechanics (or motion), obeys the relativity principle—meaning that the laws of mechanics are the same in all uniformly moving reference frames. As far as mechanics is concerned, the statement “I am moving” is meaningless; only relative motion matters.

The other branch of physics, electromagnetism, does not seem to obey the relativity principle. This means that the laws of electromagnetism, including the prediction that electromagnetic waves move with speed c , are valid only in one frame of reference: the ether's frame. As far as electromagnetism is concerned, the statement “I am moving” is meaningful and means “I am not at rest in the ether's frame of reference.”

The other branch of physics, electromagnetism, does not seem to obey the relativity principle.

An obvious question is “Is Earth moving relative to the ether?” One possible answer is that it isn't, which leaves two possibilities. First, earth alone among all the universe is at rest with respect to the ether. This follows because all the other planets, stars, galaxies, and so on are moving relative to Earth. This possibility flies in the face of the Copernican notion that Earth isn't special; this idea is also ruled out by observational evidence.

Secondly, earth “drags” the ether in its local vicinity with it. The observed *aberration of starlight* rules this out. A good analogy is the example of using an umbrella to keep dry. If you run through the rain, then you need to hold the umbrella at an angle to keep dry. But if you “drag” the air in your vicinity

with you, then the rain will fall vertically even if you run, and you won't need to tilt the umbrella. Similarly, because of Earth's motion around the Sun, a telescope will need to be pointed at different angles at different times of year to see the same star—provided Earth does not drag the ether with it. But if there is “ether drag,” then the telescope angle will not need to be changed. In fact, the telescope angle must be changed—showing that Earth does not drag ether with it.

Where does this leave us? By Copernican principles and sufficient observational evidence, we have rejected the possibility that air is moving relative to the ether. We have also determined by this point that the Earth is not dragging the ether with it. Therefore, Earth must be moving relative to the ether, and we should be able to detect this motion. ■

Essential Reading

Hey and Walters, *Einstein's Mirror*, Chapter 2 through pp. 29–36.

Hoffmann, *Relativity and Its Roots*, Chapter 4.

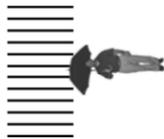
Suggested Reading

Einstein and Infeld, *The Evolution of Physics*, Chapter 3, through p. 160.

Questions to Consider

1. You might be thinking, “This ether sounds like a farfetched idea. Maybe it just doesn't exist.” How, then, would you answer the question “With respect to what does light go at speed c ?”
2. Speculate on how the success of Newton's mechanical view of the universe led physicists to embrace the ether concept.

Aberration of Starlight: Umbrella Analogy



A) Standing Still. The man and the umbrella are both at rest with respect to the rain.



B) Running. Tilting the umbrella gives the best protection from the rain. Viewed from the frame of reference of the rain.



B) Running. Similar to B in all respects except viewed from the frame of reference of the running man.



D) If the runner drags a large volume of air with him as he runs, then the rain falls vertically within this volume and the umbrella is best held horizontally.

Earth and the Ether—A Crisis in Physics

Lecture 6

In the previous lecture we asked the question: In what frame of reference are the laws of motion valid? And we gave the same answer we gave back in Lecture 3. And the same answer you realized was true in Lecture 1, namely, they're valid for anybody in uniform motion.

Forced to the conclusion that Earth must be moving through the ether, physicists set out to detect and measure that motion. From our perspective on Earth, our motion through the ether should manifest itself as an “ether wind.” As a result of that wind, the speed of light should be different in different directions.

In the 1880s, the American physicists Albert Michelson and Edward Morley conceived an experiment to detect the ether wind and answer the question “How is Earth moving relative to the ether?” Their experiment compared the travel times for light following two mutually perpendicular paths. It used interference of light to make a very precise comparison of the two travel times and was sensitive enough to detect motion much slower than that of Earth in its orbit around the Sun. Thus, the Michelson-Morley experiment could definitely determine Earth’s motion through the ether.

The Michelson-Morley experiment used an ingenious system of mirrors to compare the speeds of light in two perpendicular directions. It takes longer to row a boat a given distance up a river and back than it does to row the same distance across the

river and back. Similarly, it should take light different times to make a round trip of the same length parallel and perpendicular to the ether wind. The Michelson-Morley experiment sought to detect this difference. The extreme sensitivity of the experiment resulted from its use of *interference* between

The Michelson-Morley experiment used an ingenious system of mirrors to compare the speeds of light in two perpendicular directions.

the two light beams. The experiment did not actually measure speeds for the light beams, but rather was sensitive to *differences* in speed.

Michelson and Morley performed their experiment with the apparatus in many different orientations. They also performed it at different times of year, corresponding to different directions of Earth's orbital motion (relative to the hypothetical "ether wind"). But there was never any change in the interference pattern—meaning that Michelson and Morley could not detect any motion of Earth through the ether.

This "null result" gave rise to a serious contradiction. The Copernican paradigm and astronomical observations (especially aberration of starlight) rule out Earth's being at rest with respect to the ether. The Michelson-Morley experiment appears to rule out Earth's moving with respect to the ether.

In attempts to salvage the ether concept, the Irish physicist George Fitzgerald and the Dutch physicist Hendrik Lorentz independently proposed that objects shrink in the direction of their motion through the ether. This shrinkage was such that the Michelson-Morley light path parallel to the ether wind would be shorter by just the right amount to keep the travel time for the two perpendicular light beams the same—ensuring that the experiment could never detect motion through the ether. The Lorentz-Fitzgerald proposition had no physical or conceptual justification whatsoever; it was just an ad hoc assumption designed to explain away the Michelson-Morley result. ■

Essential Reading

Hey and Walters, *Einstein's Mirror*, Chapter 2, pp. 38–45.

Hoffmann, *Relativity and Its Roots*, Chapter 4, pp. 75–80.

Suggested Reading

Einstein and Infeld, *The Evolution of Physics*, Chapter 3, pp. 160–186.

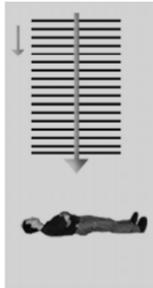
Questions to Consider

1. Did the Michelson-Morley experiment actually determine values for the speed of light in two different directions? If not, what did it measure?
2. Why was it necessary to repeat the Michelson-Morley experiment at different times of the year and with the apparatus in different orientations?
3. It is not necessary for the two arms of the Michelson-Morley apparatus to be the same length. Why not?

Wave Speed Depends on the Wind Speed and Direction



The air (represented by the gray square) is at rest relative to the viewer. The sound waves move toward the viewer at a speed of 700 mph relative to the air *and* the viewer.

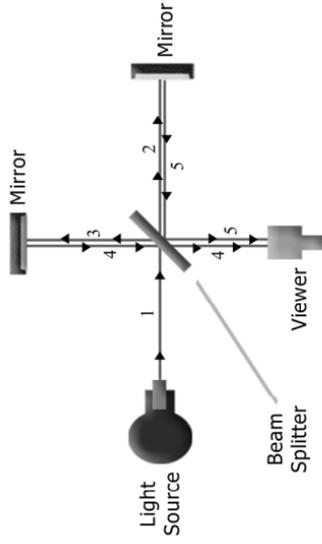


The air moves toward the viewer at a speed of 50 mph. The sound, traveling through the medium of the air, is thus moving toward the viewer with a speed of 750 mph.



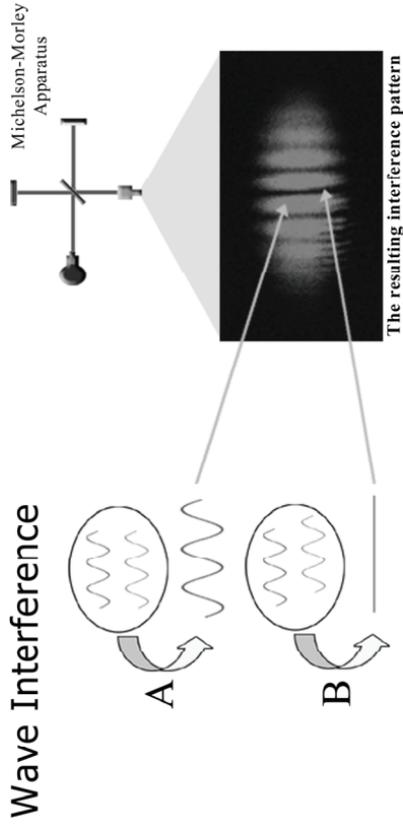
The air moves away from the viewer at a speed of 50 mph. The sound, traveling through the medium of the air, is thus moving toward the viewer at the reduced speed of 650 mph.

The Michelson-Morley Experiment



The Michelson-Morley experiment was an ingenious device for detecting the movement of an hypothesized "ether" medium with respect to the earth. With this elaborate device, a single beam of light (1), emanating from the light source (far left), is split by a beam splitter (center) into two beams (2 and 3) and through the use of mirrors (top and far right) is recombined into a single beam (4 and 5) aimed at a viewer (bottom).

The experiment relies not on precision timing of the separate light beams, but rather on the interference pattern created by the recombined light.



Wave interference, caused by two or more different waves combining, can have several possible outcomes, two of which are pictured here. In A, two light waves combine with wave troughs and wave crests coinciding, resulting in a wave with a higher amplitude. This is called **Constructive Interference**. In B, two light waves combine with troughs in the upper wave coinciding with wave crests in the bottom wave, resulting in a cancellation of the wave. This is called **Destructive Interference**.

Einstein to the Rescue

Lecture 7

It's now the year 1905, and physicists have been puzzling for several decades over the null result of the Michelson-Morley experiment. Why was there no fringe shift? Why didn't we detect the Earth's motion relative to the ether? The best we have going is the Lorenz-Fitzgerald contraction hypothesis suggesting the apparatus got compressed.

In 1905, after 10 years of pondering the nature of light and of time, Einstein resolved the contradiction with his *special theory of relativity*. As early as age 16, Einstein had puzzled about what a light beam would look like if one ran alongside it at speed c —a puzzle that he eventually solved with relativity. Einstein was 26 and a young father at the time of his 1905 paper on special relativity. He was working in the Swiss patent office because he had not been able to secure an academic position. In that same year, he published three other scientific papers, two of which were also seminal works. One provided the final convincing evidence for the existence of atoms, and the other helped lay the groundwork for quantum physics.

Even though I have stressed the logical dilemma posed by the Michelson-Morley result, historians of science debate whether Einstein even considered this result in developing his theory of relativity. Einstein's reasoning was based at least as much on how he felt nature should be as it was on experimental results.

Einstein declared the ether to be a fiction in his paper "On the Electrodynamics of Moving Bodies." Instead, he asserted the principle of relativity for all of physics, electromagnetism as well as mechanics. Thus, the essence of Einstein's theory is summed up in a single statement, the *principle of special relativity*: *The laws of physics are the same for all observers in uniform motion.* What's *special* about special

As early as age 16, Einstein had puzzled about what a light beam would look like if one ran alongside it at speed c —a puzzle that he eventually solved with relativity.

relativity is the restriction to the case of uniform motion (later, we will take up the general theory, which removes this restriction).

(As a historical note, Einstein actually proposed two postulates as the basis of his theory: the principle of relativity and the constancy of the speed of light. A more modern approach is to consider the latter a consequence of the former.)

Einstein's relativity is both radical and conservative—conservative because it asserts for electromagnetism what had long been true in mechanics, namely that motion doesn't matter (recall Galilean relativity from Lecture 3). Relativity is radical because it radically alters our notions of time and space. From a modern perspective, Einstein's relativity should come as no surprise. You already agreed to the principle of relativity in Lecture 1, when you recognized that both tennis (mechanics) and microwave ovens (electromagnetism) should work the same in any uniformly moving reference frame. Special relativity is really more than a theory; it has been verified and is unlikely to be refuted.

Why did it take a genius like Einstein to recognize the truth of relativity? Because relativity requires us to relinquish deeply ingrained ideas about space and time. The principle of relativity means that the laws of physics are exactly the same for all observers in uniform motion. In particular, the predictions of Maxwell's electromagnetic equations will be the same for all observers.

One such prediction is the existence of electromagnetic waves—including light—that travel with speed c . Therefore, all observers will measure the same value c for the speed of light—even though *different observers are moving with respect to (or relative to) each other!*

To see what this means, imagine I'm standing by the roadside, equipped with a device for measuring the speed of light. The device uses a very fast clock to time the passage of light over a known distance of exactly 1 meter. You drive by in a car at 70 mph that is equipped with an identical apparatus. Down the road, a traffic signal flashes, and we both measure the speed of the light as it passes us. Despite the fact that we're in relative motion, we both

get exactly the same speed for the light! We get the same results if we repeat the experiment with you going past in a jet plane at 600 mph or even in a spacecraft at half the speed of light! How can this be? It's possible only if our measures of time and space are different. Time and space are not absolute, but are relative to a particular observer. ■

Essential Reading

Hoffmann, *Relativity and Its Roots*, Chapter 5, pp. 81–95.

Mook and Vargish, *Inside Relativity*, Chapter 3, Sections 1–6.

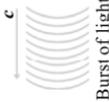
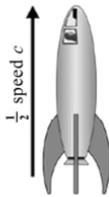
Suggested Reading

Einstein and Infeld, *The Evolution of Physics*, Chapter 3, pp. 187–209.

Questions to Consider

1. The speed of light is the same for anyone who cares to measure it. Explain how this fact follows from the principle of relativity.
2. The observer standing by the roadside in our example measures c for the speed of the light from the traffic signal. If you didn't know about relativity, what speeds would you infer for the light as measured by observers in the car, the airplane, and the spaceship?
3. What's wrong with the following explanation of the fact that all observers in our example get the same value for the speed of light? "Strange things happen to time and space when you move, so the moving observers' clocks and meter sticks are distorted in just such a way that they all get the same value for the speed of light as does the stationary observer."

Measuring the Speed of Light

	 <p>Burst of light</p>	 <p>Light Source</p>	<p>Here, the observer is standing still and records a speed of $186,000$ m/s (c) for a burst of light from the traffic signal.</p>
 <p>70 mph</p>			<p>Now, the observer is riding in a car, driven at 70 mph toward the traffic signal. When she measures the speed of light, it still comes out to $186,000$ m/s.</p>
 <p>600 mph</p>			<p>Here, the observer is riding in an airplane, flying at 600 mph toward the traffic signal. When she measures the speed of light here, it <i>still</i> comes out to $186,000$ m/s.</p>
 <p>$\frac{1}{2}$ speed c</p>			<p>Finally, the observer is riding in a spaceship, traveling at one half the speed of light toward the traffic signal. When she measures the speed of light here, it <i>still</i> comes out to $186,000$ m/s. The speed of light is the same in all frames of reference.</p>

Uncommon Sense—Stretching Time

Lecture 8

How can it be that if you move past me at half the speed of light, and we measure the speed for the same light beam, that we get the same value when you're moving relative to me at such a high speed? It violates everything we know from our common sense. How can it possibly be?

The simple statement of relativity—that the laws of physics are the same for all observers in uniform motion—leads directly to absurd-seeming situations that violate our commonsense notions of space and time. But common sense is built of our limited experience, in which we never move at speeds anywhere near c relative to things in our immediate environment.

Our common sense isn't wrong; it's just an approximation that works when relative speeds are small compared with c . We simply don't move at speeds anywhere near c relative to the objects with which we interact. (We do move at speeds near c relative to distant galaxies and cosmic rays, but most of us aren't directly aware of that.) To describe the universe accurately and to understand what happens at high relative speeds, we need to abandon common sense and instead embrace the principle of relativity. When we do, we find that measures of time and space differ in different frames of reference.

It is all too easy to speak in a way that violates the principle of relativity; even many books on the subject do. We need to make an effort to be *relativistically correct* (RC) in describing what happens to space and time. In the traffic light example, for instance, I can't dismiss your strange clock readings because "you're moving." That's because the principle of relativity denies the concept of absolute motion. Both of us are equally positioned for doing physics, and your measurements in the spaceship zooming past Earth at $0.5c$ are every bit as good as mine on Earth. It could be that the different clocks keep different time.

Let's consider the concept of "time dilation" or the stretching of time. A "light clock" consists of a box containing a light source at one end and a mirror at the other. A flash of light leaves the source, bounces off the mirror, and returns to the source. This process repeats, so the round-trip travel time for the light constitutes the basic "ticking" of this clock. We want to examine the length of this "ticking"—that is, the time between the event of light leaving the source and returning to the source—in two different frames of reference.

First let's define "event": An event is something that happens at a time and a place. To an observer at rest with respect to the light clock, the light makes a round-trip journey twice the long dimension of the box. To an observer relative to whom the box is moving, the light takes a longer path, following two diagonals that are each longer than the long dimension of the box. Here's where relativity comes in: The speed of the light is the *same* for both observers. Because the path lengths for the light are different, however, so must be the times between the emission of the light and its return to the source!

The phenomenon of different times for different observers of the light clock is called *time dilation*. There's nothing special about the light clock; it's just a convenient device for visualizing why time dilation occurs. Times on ordinary clocks would show the same discrepancy. Time dilation is not about light or light clocks; it's about *time itself*. Measures of time are simply different for different observers in motion relative to each other—a consequence of the principle of relativity.

Time dilation is often described by saying that "Moving clocks run slow," but this is very poor wording and not RC. Why not? Pause a minute and think about that question before proceeding. In particular, an observer moving with the light clock would feel *nothing unusual whatsoever!* Things wouldn't seem to be happening in slow motion nor would anything else seem strange. The frame of reference of the light clock is just as good as any other uniformly moving frame, so all physical events happen perfectly normally.

What time dilation really says is this: Suppose there are two events that occur at different places in some frame of reference; in that reference frame, the

time between the events is measured by a pair of clocks at the two different places. If another clock moves so that it is present at both events, then the time between the events as measured on that single clock will be less than that measured by the pair of clocks.

Let's try a quantitative example. Let t' be the time measured by the observer at rest with respect to the light clock, and t , the time measured by the observer for whom the box is moving. Then the two times are related by $t' = t\sqrt{1-v^2}$ where v is the speed of the light clock relative to the observer for whom it's moving, with v given as a fraction of the speed of light (i.e., $v = 0.5$ is half the speed of light). Anyone who remembers the Pythagorean theorem and who is fluent in high school algebra can derive this result, but we'll leave that as an exercise for those who want to try it. ■

Essential Reading

Hey and Walters, *Einstein's Mirror*, Chapter 3, pp. 46–55 (but watch out for relativistically incorrect wording in one heading!).

Hoffmann, *Relativity and Its Roots*, Chapter 5, pp. 96–106.

Mook and Vargish, *Inside Relativity*, Chapter 3, Sections 7–10.

Suggested Reading

Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy*, Chapter 1.

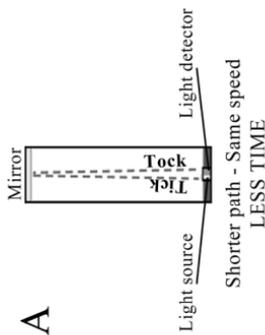
Questions to Consider

1. What's wrong with the statement "Moving clocks run slow"? Can you find this or a similar "relativistically incorrect" statement in a book on relativity?

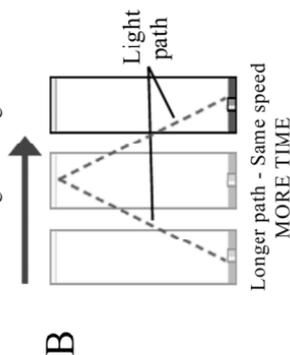
2. (For the mathematically courageous; you need not be able to do this to understand relativity!) Using high-school algebra and the Pythagorean theorem, derive the time-dilation equation $t' = t\sqrt{1-v^2}$.

Time Dilation : A "Light Clock"

In a frame of reference at rest with respect to the light clock:



In a frame of reference in which the light clock is moving to the right:



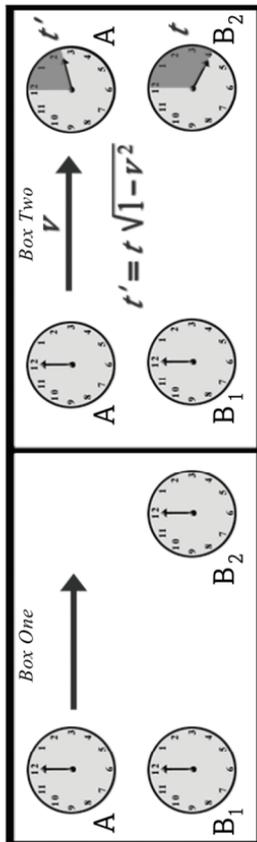
The light clock is a device that clearly shows how time dilation occurs. In this device, light is produced from a light source at the bottom of the clock, travels up the length of the light clock, bounces off a mirror, and returns to hit a light detector on the bottom of the clock. In A, a frame of reference in which the light clock is at rest with respect to the viewer, the path of the light is exactly equal to twice the height of the clock. In B, a frame of reference in which the light clock is moving to the right with respect to the viewer, the light path is longer. *But the speed of light has the same value for both observers* and thus the time as measured in frame B is longer than the time recorded by clock A.

TIME DILATION

—“Moving clocks run slow.”— **Bad Wording: Not RC!**

The time between two events is shorter when measured by a single clock present at both events than when measured by two different clocks located at the two events.

In this diagram, time dilation is explained in terms of “real” clocks rather than light clocks. Box One sets the stage for the experiment. Two clocks (B_1 and B_2) are located at two different places. Clock A is a clock whose state of motion is such that it will be present at B_1 and then later will be present at B_2 . The two events that we are interested in are the concurrence of A with B_1 and the concurrence of A with B_2 . Time dilation states that the time elapsed as recorded by clock A which is present at both events will be less than the elapsed time as recorded by the two other clocks. Box Two shows the results: t' is the elapsed time recorded by A. t is the elapsed time as recorded by the two B clocks. The equation in the center of Box Two describes the mathematical relationship between t' and t .



Muons and Time-Traveling Twins

Lecture 9

Measures of time between two events simply are not absolute. Now, I grant that you probably have great difficulty accepting this intuitively, because all your experience suggests that to say this class is one hour long, or this lecture is a half hour long, or this airplane flight is two hours long, that that has an absolute meaning. It doesn't.

Experiments with subatomic particles called muons dramatically confirm that time dilation really occurs. These particles are produced in the upper atmosphere and travel downward at nearly the speed of light. But they're radioactive, and they decay in such a short time that they shouldn't last long enough to make it to the ground. Yet they do—showing that time runs slower in the muons' frame of reference by just the amount expected from time dilation.

Muons are subatomic particles produced by cosmic rays high in Earth's atmosphere. They rain down on Earth at a steady rate and can, therefore, be considered "clocks." The muons are radioactive and decay in a time so short that very few should be expected to reach sea level.

In the 1950s, physicists measured the number of muons arriving each hour atop Mount Washington in New Hampshire; it was about 600 per hour. These muons were moving at $0.994c$ and, even at that high speed, their radioactive decay meant that only about 25 should survive to sea level. But a measurement at sea level revealed about 400 muons each hour. This is consistent with time in the muons' frame passing at about $1/9$ the rate it does on Earth. Work out the quantity $\sqrt{1-0.994^2}$ and you will see that it is just about $1/9$. So time dilation really happens!

Here is another example: Suppose we had a spaceship capable of $0.8c$ relative to Earth. It sets out on a trip to a star 10 light-years distant (one light-year is the distance light travels in a year, so the speed of light is simply 1 light-year/year). From the Earth's point of view, the ship is going 10 light-years at 0.8 light-years/year. Because distance

= speed \times time, the time this takes is $t = 10 \text{ ly} / 0.8 \text{ ly per year} = 12.5$ years. But according to time dilation, the time on the ship is: $t' = (12.5 \text{ years}) \times \sqrt{1 - 0.8^2} = (12.5 \text{ years}) \times (0.6) = 7.5 \text{ years}$

Similar to this example, the “Twins Paradox” is a famous seeming paradox of relativity. Imagine the same star trip, but now the ship turns around once it reaches the star. The return trip is just like the outbound trip, so it takes 12.5 years according to observers on Earth and 7.5 years in the ship. When the traveling twin returns, she is 15 years older, but her brother is 25 years older!

Why can’t the traveling twin consider that she’s at rest and that Earth goes away on a 10-light-year journey at $0.8c$, in which case she should conclude that her brother will be younger? The answer is that the situation is not symmetric.

The Earthbound twin stays all the time in a single, uniformly moving reference frame (here we neglect the nonuniform motion associated with Earth’s rotation and orbital motion; because these are slow compared with c , they don’t have a significant effect on the results).

The traveling twin occupies two different uniformly moving reference frames, going in opposite directions. They’re separated by the ship’s turnaround. The traveling twin feels that turnaround; Earth doesn’t. The situation really is different for the two twins, so there’s no paradox.

Think about what’s *special* about special relativity: It is restricted to frames of reference in *uniform* motion. The statement “I am moving” is meaningless according to the principle of relativity, but the statement “My motion changed” is meaningful. Here, the traveling twin can rightly say, “My motion changed,” but the Earthbound twin cannot.

The twins’ experiment actually has been done, but with an atomic clock flown around the Earth.

By going faster, the traveling twin could make her trip time arbitrarily small; as v approaches the speed of light c (or v approaches 1 in our formula), the time-dilation factor $\sqrt{1-v^2}$ approaches 0. If she goes at very nearly c , the trip will take just barely over 25 years' Earth time, but a negligibly small amount of ship time—so she will return 25 years younger than her twin.

By going farther, the traveling twin can go further into the future. Suppose she goes to the Andromeda galaxy, 2 million light-years distant, at nearly c . The shortest Earth time a round trip can take is just over 4 million years, but the ship time can be arbitrarily small. So she can return to Earth 4 million years in the future. But this is a one-way trip! If the traveling twin does not like what she finds, there is no going back! Time travel to the past is not permitted.

Can we hope to duplicate the twin's trip? Not with today's spacecraft. Scientists have sent an atomic clock on a round-the-world airplane trip. On return, it read less time—by some 300 nanoseconds (300 billionths of a second)—than its stay-behind twin. The effect is clearly measurable but hardly dramatic, because the airplane's speed is so much less than that of light. This experiment actually involves effects of both special and general relativity, as we'll see in subsequent lectures. ■

Essential Reading

Hey and Walters, *Einstein's Mirror*, Chapter 3, pp. 64–66.

Hoffmann, *Relativity and Its Roots*, Chapter 5, pp. 109–110.

Mook and Vargish, *Inside Relativity*, Chapter 4, pp. 110–111.

Suggested Reading

Davies, *About Time: Einstein's Unfinished Revolution*, Chapter 2.

Fritsch, *An Equation that Changed the World*, Chapter 11.

Hafele and Keating, “Around-the-World Atomic Clocks: Predicted Relativistic Time Gains” and “Around-the-World Atomic Clocks: Observed Relativistic Time Gains,” *Science*, vol. 177, pp. 166–170 (July 1972).

Moore, *A Traveler’s Guide to Spacetime*, Sections 4.7.3 and 5.8.

Taylor and Wheeler, *Spacetime Physics*, 2nd edition, Chapter 4.

Questions to Consider

1. Suppose two triplets leave Earth at the same time and undertake round trip space journeys of identical length and at the same speed but in opposite directions. When they return, will they be the same age or will one be older? How will their ages compare with their third sibling, who stayed at home on Earth?
2. In 1999, scientists discovered a planetary system orbiting a star 44 light-years from Earth. How far into the future could you travel by taking a high-speed trip to this star and returning immediately back to Earth? Under what conditions would you achieve this maximum future travel? How long would you judge the trip to take?
3. Suppose the twin in the spaceship traveled at $0.6c$ instead of $0.8c$. By how much would the twins’ ages differ when the traveling twin returns to Earth?

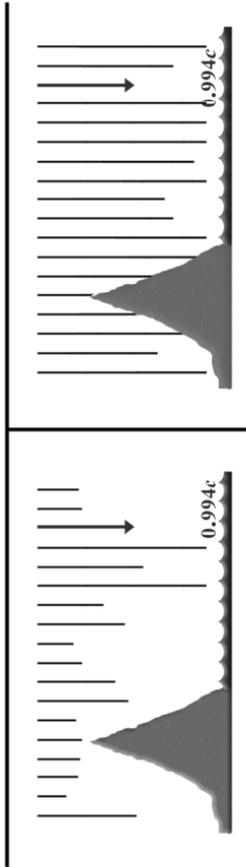
Time Dilation : An Experiment with Muons

In this experiment subatomic particles called muons, which have a fixed rate of decay, stream down from high in the atmosphere toward earth at a speed of $0.994c$. The experiment has two stations, one at the top and one at the bottom of the mountain, that measure the number of muons passing by.

In the first box, we see the results that would be expected if time dilation did not occur.

As the muons stream down toward earth, many are detected at the top of the mountain in the first station. But since muons decay at such a rapid rate, the expected count of muons passing the second station at the bottom of the mountain is dramatically lower.

In the second box we see the results as they actually do occur, with time dilation affecting the results. Since the muons are traveling at a significant fraction of the speed of light ($0.994c$), their measure of elapsed time is significantly slower than the time recorded by the two stations. Thus, with the muons' time running more slowly, most of them do indeed reach the second station.



A Little Math...

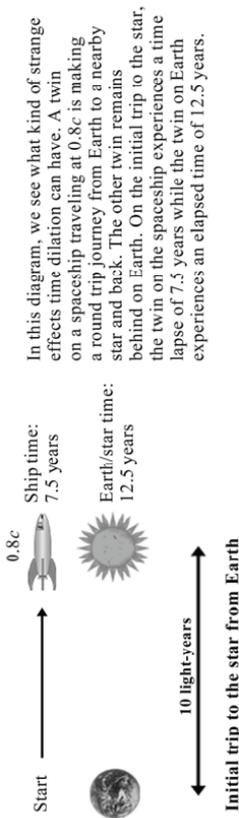
Distance = speed \times time, so in Earth-star frame of reference, trip takes:

$$t = \frac{d}{v} = \frac{10 \text{ light-years}}{0.8 \text{ light-years / year}} = 12.5 \text{ years}$$

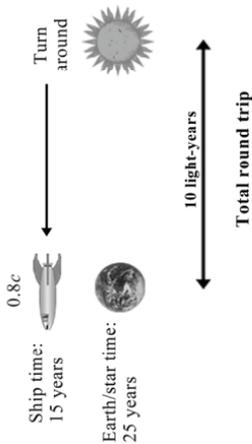
Time dilation: $t' = t \sqrt{1-v^2}$,
so in ship frame, trip takes:

$$\begin{aligned} t' &= (12.5 \text{ years}) \sqrt{1-0.8^2} \\ &= (12.5 \text{ years}) (0.6) = 7.5 \text{ years} \end{aligned}$$

Star Trip!



On the return trip, the twin in the spaceship experiences another 7.5 years of elapsed time for a total elapsed time of 15 years, and the twin on Earth experiences another 12.5 years of elapsed time for a total elapsed time of 25 years. The twin in the rocketship returns 10 years younger than the twin who remained on Earth!



Escaping Contradiction—Simultaneity Is Relative

Lecture 10

Most of the contradictions are resolved by a fact that's spelled out in the second half of my title, namely, that simultaneity is relative. What it means to say that two events are simultaneous—occur at the same time—actually depends on your frame of reference. And we're going to explore that in some detail in this lecture.

There seems to be a big problem with time dilation: “Moving clocks run slow,” but who's to say which clock is moving? If clock B sees clock A move by and concludes that clock A is “running slow,” why can't clock A claim to see clock B go by and conclude that B is “running slow”? It can! There's no contradiction, because of another remarkable implication of the principle of relativity: Two events that are simultaneous (i.e., that occur at the same time) in one frame of reference are not simultaneous in another frame that is moving relative to the first. It is this relativity of simultaneity that allows two observers in relative motion to see each other's clocks “run slow” without contradiction.

Recall that we arrived at time dilation by considering *one* clock that moves past *two* others that are at rest relative to each other and that are *synchronized*—meaning the events of their hands pointing to a given time are simultaneous. Those events are simultaneous in the clocks' own frame. Remarkably, as we'll see shortly, relativity implies that events simultaneous in one frame of reference are not simultaneous in another frame.

They are not simultaneous in the frame of the “moving” clock. In fact, the right-hand clock reads a later time, and that is why the elapsed time on the two clocks is longer than on the “moving” clock, even though the “moving” clock judges the other two to be “running slow.” There is no contradiction; observers in each frame judge the other's clocks to be “running slow,” and each is correct. In general, the relativity of simultaneity explains many of the apparent paradoxes that arise in relativity. They are only paradoxical if one insists that simultaneity is an absolute concept—and it isn't.

To understand why simultaneity is relative (or why events that are simultaneous in one frame of reference are not simultaneous in another frame of reference), we will revisit the star trip example that we discussed earlier. This example reveals the phenomenon of *length contraction*. Earth–star distance was 10 light-years in the Earth–star frame. But the spaceship made the trip in 7.5 years, going at $0.8c$. Therefore, in the ship frame, the distance must have been $(0.8 \text{ ly/y}) \times (7.5 \text{ years}) = 6 \text{ light-years}$.

In general, the length of an object is longest in a frame in which the object is at rest. (Here, the “object” is the Earth–star system, 10 light-years long to an observer at rest in that frame.) An object is shorter when measured in a frame of reference in which it is moving, with the contraction given by the same factor $\sqrt{1-v^2}$ that arises in time dilation. This is called “Lorentz contraction” (or sometimes “Fitzgerald contraction”). Recall from Lecture 6 that they came up with the right idea for the wrong reason.

An example in which length contraction is important is the Stanford Linear Accelerator, which is 2 miles long as measured on Earth, but only about 3 feet long to the electrons moving down the accelerator at $0.9999995c$. Even a TV picture tube, in which electrons attain about $0.3c$, would not focus correctly if engineers did not take length contraction into account.

If we are being relativistically correct, then isn’t the distance between Earth and star really 10 light-years and the length of the Stanford Linear Accelerator really 2 miles? No! To claim so is to give special status to one frame of reference, and that is precisely what relativity precludes. Be careful of using the word “really” when talking about relativity.

To examine the relativity of simultaneity further, consider two very high-speed airplanes passing each other in opposite directions. There is some frame of reference in which both have the same speed and, therefore, the same length (although it is shorter than their length at rest). In this frame,

Remarkably, as we’ll see shortly, relativity implies that events simultaneous in one frame of reference are not simultaneous in another frame.

the left ends of the two planes coincide at the same time that the right ends coincide; the events of the two ends coinciding are, therefore, simultaneous.

In a frame in which the upper airplane is at rest, the right ends of the two planes coincide before the left ends, so the events aren't simultaneous. In a frame in which the lower airplane is at rest, the time order of the two events is reversed. Continuing this line of reasoning, would it be possible for your birth and death to occur at the same time?

Is there a problem with causality? After all, if the time order of events can be reversed in different reference frames, there might be. But there is no problem; we'll see why in the next lecture. ■

Essential Reading

Mook and Vargish, *Inside Relativity*, Chapter 4, pp. 111–113.

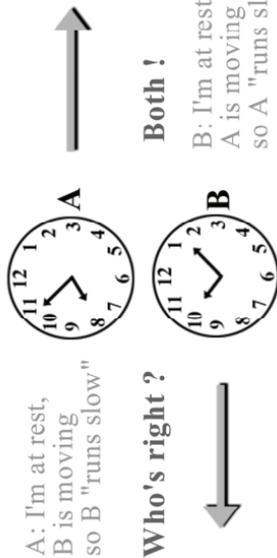
Suggested Reading

Moore, *A Traveler's Guide to Spacetime*, Chapter 3.

Questions to Consider

1. Devise an experiment that observers in the reference frame of clock A could do to verify that, as measured in the upper clock's frame, both the clocks in the lower frame are "running slow."
2. A famous "paradox" of relativity is the following: A high-speed runner carries a 10-foot-long pole toward a barn that is 10 feet long and has doors open at both ends. The runner is going so fast that, from the point of view of the farmer who owns the barn, the pole is only 5 feet long. Clearly, the farmer can close both barn doors and trap the runner in the barn. But to the runner, the pole is 10 feet long and the barn, rushing toward the runner, is only 5 feet long. So clearly the runner can't be in the barn with both doors closed. Can you resolve the paradox, using the fact that events simultaneous in one reference frame aren't simultaneous in another? (By the way, the speed required here is $0.866c$.)

Who's Moving? Who's "Running Slow"?



This diagram illustrates what initially seems to be a contradiction created by the Principle of Relativity. Because the laws of physics are valid in all frames of reference in uniform motion, observers in the reference frame of each clock can draw the same conclusions about the other clock. Thus the following statements hold:

- #1. From a frame of reference in which Clock A is at rest, Clock B is in motion and thus is "running slow" compared to Clock A.
- #2. From a frame of reference in which clock B is at rest, Clock A is in motion and thus is "running slow" compared to Clock B.

The two statements seem to be completely contradictory, but relativity insists that both are correct. The explanation lies in the fact that simultaneity itself is actually relative, as can be seen in Dr. Wolfson's later arguments.

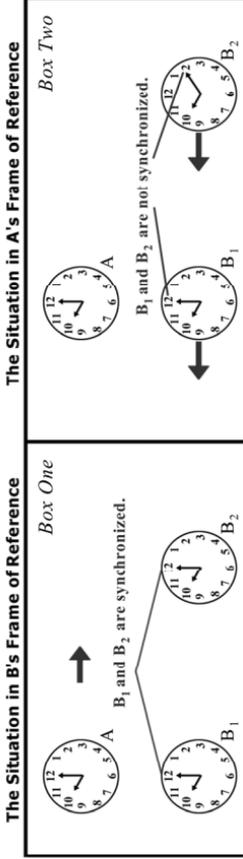
The Situation in Different Frames of Reference

This diagram illustrates the same experiment, viewed from two separate frames of reference. In the experiment, clock A moves from clock B₁ to clock B₂, similar to the experiment in Lecture 8.

Box One details the experiment as seen from the frame of reference of clocks B₁ and B₂. In this frame, the two clocks are synchronized and an observer in the B-clock frame can conclude that clock A "runs slow" as it moves between B₁ and B₂.

Box Two details the exact same experiment from the frame of reference of Clock A. To observers in this frame, the B clocks are running slow.

The problem of contradiction is resolved through the concept of relative simultaneity. While the B clocks are synchronized in *their* frame of reference, they are *not* synchronized in A's frame of reference. Although they're "running slow," clock B₂ is ahead and thus the elapsed time (B₂ - B₁) is still longer than that measured on clock A.



Star Trip, Revisited

In spaceship's frame of reference:
Earth-star trip takes 7.5 years at $0.8c$

Therefore distance is:

$$\begin{aligned} \text{distance} &= \text{speed} \times \text{time} \\ &= (0.8 \text{ ly/y}) \times (7.5 \text{ years}) \\ &= 6 \text{ light-years} \end{aligned}$$



Two Identical Airplanes Pass

In a frame where both are moving, their ends coincide at the same time:



In a frame where the upper plane is at rest, their right ends coincide first:



In a frame where the lower plane is at rest, their left ends coincide first:



Faster than Light? Past, Future, and Elsewhere

Lecture 11

The fact [is] that events that are simultaneous in one frame of reference are not simultaneous in another, and, in fact, that the time order of those events is also relative. Event A may occur before event B in one frame of reference, and event B before event A in another frame of reference. How can these things be?

That the time order of events can be different in different reference frames seems to wreak havoc with cause and effect. Is there some frame in which your death precedes your birth, for example? No, the only events for which the time order can be different are those that occur far enough apart in space that it would be impossible for a light signal to get from one event to the other.

Time between any two events depends on the frame of reference from which the events are measured (as time dilation examples show). To clarify, an *event* is specified by giving both a place and a time. However, the *time order* of events can differ in different reference frames only if the events are far enough apart in space that not even light travels fast enough to get from one event to another. Because nothing can travel faster than light (more on this shortly), the two events cannot be causally related. Thus, there is no problem with causality. For example, when the Mars Rover was active in the late 1990s, Earth and Mars were 11 light-minutes apart. An event on Earth and one occurring 5 minutes later (Earth–Mars time) on Mars cannot be causally related—and there can be observers for whom the Mars event occurs first. (But doesn't the Earth event *really* occur first? That question is not RC! Think about why not.) Such causally unrelated events define a new realm of time, in addition to past, present, and future.

In relativity, the past consists of those events that can influence the present. For example, your birth is in part the cause of your now watching or listening to these lectures. It is in your past, and all observers will agree that it came before your present moment (although they will disagree about the amount of time between your birth and now). But an event simultaneous with your

birth (simultaneous in Earth's frame of reference) at the center of our galaxy, 30,000 light-years away, is not in the past because it can't yet affect us.

Similarly, the future consists of events that the present can influence. Events that will happen tomorrow on Earth are in the future, and all observers will agree that events on Earth today come before those on Earth tomorrow. However, events that will happen tomorrow at the galactic center are not in the future of the present moment on Earth, because there is no way we can influence them.

Those events that are neither in the past nor the future are in the *elsewhere*. They can have no causal relation to the event here and now, and different observers will judge differently whether they occur before, after, or are simultaneous with the here and now. The elsewhere is not some mysterious realm, forever inaccessible; it's just inaccessible to the here and now. Events that are now in your elsewhere will sometime later be in your past and, at some earlier time, they were in your future. But there's a band of time centered on the present—22 minutes for Mars, 60,000 years for the galactic center, 4 million years for Andromeda—during which events are unrelated to the here and now. Again, this gives us a new realm of time to go with our categories of past, present, and future.

All this depends on nothing being able to go faster than light. But why is it impossible to go faster than light? It follows from the principle of relativity that light goes at speed c relative to any uniformly moving reference frame. Therefore, there cannot be an observer who is at rest with respect to light. Because you would need to reach the speed of light to go faster still and because you can't be at rest with respect to light, then you can't go faster.

More technically, a light wave at rest is simply not a solution to Maxwell's equations of electromagnetism; only a light wave moving at c is. Accepting the principle of relativity—that all of physics, including Maxwell's

In relativity, the past consists of those events that can influence the present. For example, your birth is in part the cause of your now watching or listening to these lectures.

equations—is valid in all reference frames, then it is impossible to be at rest relative to light and, therefore, impossible to go at speed c . (This is the point Einstein puzzled about at age 16.) Attempting to travel faster than light by “leapfrogging” from one rapidly moving reference frame to another fails, because measures of time and space differ in different reference frames. A more precise statement about faster-than-light travel is that no *information* can be transmitted at speeds faster than light.

Is this something special about light? No, it’s about *time*; light only provides the extreme case. If a police car going 50 mph clocks you going 30 mph relative to the police car, are you going 80 mph relative to the road? Not quite! The difference is tiny, but it is there and it results from the fact that measures of time and space are different in the different reference frames. As speeds approach c , the effects of this *relativistic velocity addition* become more dramatic and prevent any material objects ever moving at c relative to each other.

There is one important caveat: It is the speed of light *in vacuum* that is the ultimate speed. Light moves slower through transparent materials, such as glass, water, or even air—and there’s no problem with objects moving faster than the speed of light in such materials. High-energy subatomic particles moving through water, for example, often do exceed the speed of light in water and, when they do, they produce shock waves analogous to the sonic booms from supersonic aircraft.

A more sophisticated description of c is not so much that it’s the speed of light but rather that it’s a conversion factor between units of space and time. If we really wanted to be relativistically correct, we would measure time and space in the same units and c would have the value 1. ■

Essential Reading

Hey and Walters, *Einstein’s Mirror*, Chapter 4.

Hoffmann, *Relativity and Its Roots*, Chapter 5, pp. 121–127.

Suggested Reading

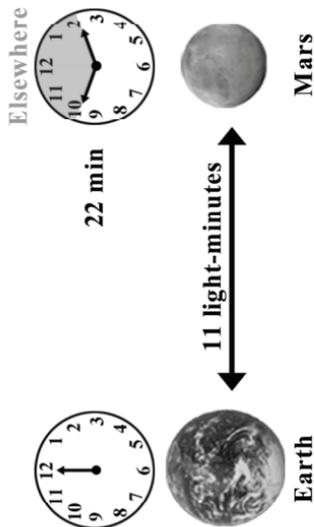
Moore, *A Traveler's Guide to Spacetime*, Chapter 8, Section 4.

Taylor and Wheeler, *Spacetime Physics*, Chapter 6.

Questions to Consider

1. Right now it's "the present," but is it "the present" everywhere? Explain your answer.
2. Suppose a technological civilization evolved 25,000 years ago on the other side of our Milky Way galaxy, 60,000 light-years from Earth. Could there be observers for whom technological civilization emerged first on Earth? What if the extraterrestrial civilization had evolved 1 million years ago?
3. What's wrong with defining the past as those events that have already happened?

EVENTS ON EARTH AND MARS



This diagram illustrates the idea of the **Elsewhere**. The Elsewhere is a region of spacetime that is neither past nor future. The elsewhere of a given event consists of those events that cannot influence or be influenced by the given event – namely, those events that are far enough in space that not even light can travel between them and the given event.

The distance between Earth and Mars is 11 light-minutes. Events on Mars cannot influence events on Earth for a period of 11 minutes. Events on Earth cannot influence events on Mars for a period of 11 minutes. Thus there is a 22 minute interval in which events on Mars cannot influence or be influenced by the present moment on Earth. These Martian events lie in the **elsewhere** of Earth's present.

Faster than Light?



Speed of small ship
relative to Earth?

$$\cancel{1.6c} - 0.97c$$

In this diagram, the large ship is moving at $0.8c$ relative to Earth. The small ship is moving in the same direction, but at $0.8c$ relative to the large ship. Classical physics states that their velocities should be added together in order to find out how fast the small ship is moving relative to Earth. This simple addition would give the answer of $1.6c$ which is faster than the speed of light. Relativity shows that velocities do not combine in a simple addition, but in a more complicated way that does not allow a velocity combination to exceed the speed of light. In this case, the two velocities combine to produce a velocity for the small spaceship of $.97c$ relative to Earth.

What about $E=mc^2$, and Is Everything Relative?

Lecture 12

You'll notice everything I've said so far about space, and time, and causality, and past, and present, and elsewhere, and future, and so on, is without any mention of $E=mc^2$.

Shortly after publishing his 1905 paper on special relativity, Einstein realized that his theory required a fundamental equivalence between mass and energy. This equivalence is expressed in the famous equation $E=mc^2$. What this means is that an object or system of objects with mass m contains an amount of energy given by the product m multiplied by the speed of light squared. Because c is large, this is an impressive amount of energy. The energy contained in a single raisin could power a large city for a whole day.

This equation is mistakenly assumed by many to be the essence of relativity. Although the idea behind the equation is seminal, $E=mc^2$ came as an afterthought to special relativity, and it was not until 1907 that Einstein published a comprehensive paper on the subject. $E=mc^2$ asserts an equivalence between mass and energy.

$E=mc^2$ is commonly associated with nuclear energy, and Einstein's work is, therefore, mistakenly considered responsible for nuclear weapons. A historical aside: Although $E=mc^2$ and Einstein are not responsible for nuclear weapons, Einstein did have a minor role to play in the development of these weapons. Dr. Leo Szilard, a physicist who first conceived of a nuclear chain reaction, prepared a letter to President Franklin D. Roosevelt at the start of World War II urging a U.S. nuclear weapons program to counter German nuclear efforts. Szilard convinced Einstein to sign the letter. This was Einstein's only involvement with nuclear weapons. Incidentally, Szilard later founded the Council for a Livable World, which has worked for decades to oppose nuclear weapons.

Actually, rather than applying solely to phenomena involving nuclear energy, $E=mc^2$ applies to *all* energy transformations, including the chemical

reactions involved in burning coal or gasoline or metabolizing your food. Even a stretched rubber band weighs more than an unstretched one, because of the energy put into stretching it.

As mentioned above, $E=mc^2$ does also apply to the nuclear reactions that power the Sun or our nuclear reactors and weapons. In the Sun, nuclear fusion reactions convert some 4 million tons of mass to energy every second as a result of nuclear fusion in the solar interior. Even with nuclear reactions, though, only a small fraction of the total mass is converted to energy.

The most dramatic (and efficient) example of mass-energy equivalence comes from *pair creation*, the creation of a particle of matter and its antimatter opposite out of pure energy. The opposite process, annihilation, occurs when a particle and its antiparticle meet and disappear in a burst of gamma ray energy.

$E=mc^2$ provides another way of understanding why nothing can go faster than light. Because of mass–energy equivalence, energy, like mass, manifests itself as inertia, making an object harder to accelerate. As an object is accelerated to high speed, its energy increases and, therefore, so does its inertia. The object becomes harder to accelerate. Inertia increases without limit as an object’s speed approaches c . It would, therefore, take infinite force and infinite energy to accelerate a material object to the speed of light—and that is impossible.

Is everything relative, dependent on one’s frame of reference? Believing that Einstein’s work declares everything relative has sometimes been used to assert relativity in aesthetics, morality, and other humanistic areas. But even if everything in physics were relative, why should this carry implications for morality, for example?

Clearly, everything isn’t relative. The principle of relativity declares one absolute: the laws of physics. They are the same for everyone (at least, at this point, for everyone in uniform motion). A corollary of the laws of physics being absolute is that the speed of light is the same for all observers. So the speed of light is not relative.

There are other so-called *relativistic invariants* that don't depend on an observer's frame of reference. An important case is the *spacetime interval* between two events. Although different observers get different values for the

“Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.”

—Hermann Minkowski

time between two events and different distances between the events, all agree on this interval, which is a kind of four-dimensional “distance” incorporating both space and time.

An analogy—adapted from *Spacetime Physics*, by Taylor and Wheeler—is the measurement of distance between two points on Earth. To get from point A to point B, you might say “go 3 miles east, then 4 miles north.” But suppose you made your map without correcting for

the difference between magnetic and true north. Then, your map grid would be tilted, and you would describe the path from A to B differently, but the actual straight-line distance from A to B would be exactly the same.

Relativity is like that: Space is analogous to one direction, say east–west, and time, to the other (north–south). Different observers in relative motion are like the different mapmakers; each imposes a different “grid” on an underlying, objective reality. How that reality divides into space and time depends on the “grid”—that is, on the observer's state of motion; just as in the map analogy, the amount of eastward and northward motion differs with which map one uses.

There is an objective, absolute reality behind the quantities that are relative. In the map analogy, this is the distance from A to B, about which users of either map agree. In relativity, it is the spacetime interval between events. Spacetime is the name for the four-dimensional framework in which physical events occur—a framework that transcends individual observers and their different reference frames and gives the lie to the notion that “everything is relative.” In the words of Hermann Minkowski, who had been one of Einstein's mathematics professors and later worked on the mathematical aspects of relativity:

“Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality” (Hermann Minkowski, 1908, as printed in Lorentz, et al., *The Principle of Relativity*, p. 75). ■

Essential Reading

Hey and Walters, *Einstein's Mirror*, Chapters 5–6.

Mook and Vargish, *Inside Relativity*, Chapter 3, Section 11; Chapter 4, Section 5.

Suggested Reading

Davies, Paul, *About Time: Einstein's Unfinished Revolution*, Chapter 3.

Moore, *A Traveler's Guide to Spacetime*, Chapters 9–10 (requires a lot of math!).

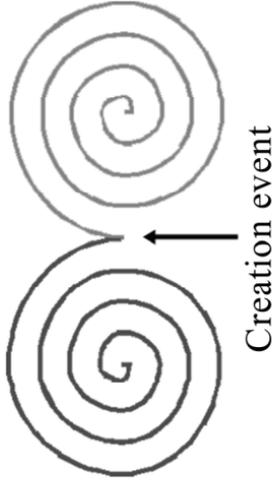
Taylor and Wheeler, *Spacetime Physics*, Chapter 1.

Questions to Consider

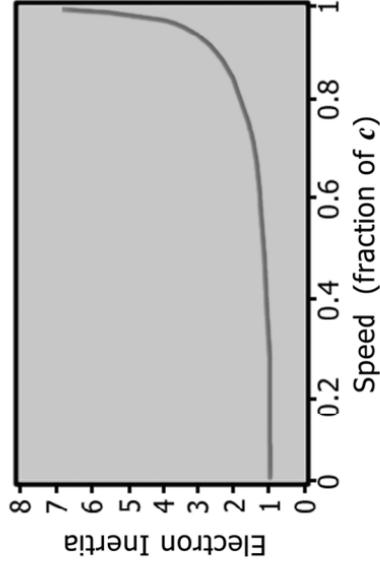
1. You throw a bunch of subatomic particles into a closed box, the walls of which block the passage of matter but not energy. Must the number of particles in the box remain the same? Explain.
2. A coal-burning power plant and a nuclear plant each put out exactly the same amount of energy each second. How do the amounts of mass that they convert to energy in the same time compare?

A Pair Creation Event

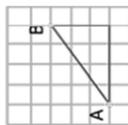
Positron's path Electron's path



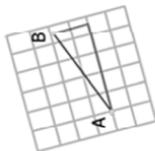
Electron Inertia Increases With Speed



Getting from A to B: The Invariance of Distance



In this first map, a mapmaker has chosen true north as his reference direction. His description of the distance from A to B is "4 units east and 3 units north."



In this second map, another mapmaker has chosen magnetic north as her reference direction. Her description of the distance from A to B is different than the description the first mapmaker gives. The second mapmaker's directions say "4.5 units east and 1.75 units north"



When we superimpose the two maps, we see that the actual distance between points A and B is the same in both maps. The directions differ from map to map but the underlying physical relationship between A and B remains unchanged.

A Problem of Gravity

Lecture 13

The general theory of relativity is, remarkably, a theory of gravity. It doesn't seem, at first, that it should be. And in this lecture, we're going to explore why that is.

The special theory of relativity is *special* because it is restricted to observers in *uniform motion*. All such observers have equal claim on the validity of the laws of physics. A *general theory of relativity* would remove the restriction to uniform motion, making the laws of physics equivalent to all observers, whatever their states of motion. We need to proceed with caution at this point: This won't be as logical as the development of special relativity; the ideas are more abstract and the mathematics best left to experts! At first, the idea of a general theory of relativity seems absurd, because we *feel* when we're in accelerated motion (a car rounding a curve, an airplane accelerating down the runway for takeoff, a ship sailing in stormy seas). Historically, general relativity arose from Einstein's attempt to reconcile gravity with the principle of relativity. The incorporation of gravity into the theory solves both the problem of accelerated motion and inconsistencies between Newtonian gravitation and the principle of relativity.

This is the problem of gravity: Newton describes gravity as a force between distant objects; e.g., between Earth and moon, Sun and Earth, or Earth (all the matter of which it consists) and you. In Newton's theory, the force of gravity somehow reaches *instantaneously* across empty space to hold the moon, for example, in its orbit. But this cannot be consistent with relativity for several reasons. Relativity precludes any information moving at speeds greater than the speed of light. Newton's instantaneous action-at-a-distance gravitational force violates the "cosmic speed limit."

Newton's gravitational force depends on the distance between two objects, a distance that often varies with time. But special relativity shows that distance is relative, as is simultaneity. So Newton's law of gravity gives different results in different reference frames and, thus, is inconsistent with the principle of relativity.

Galileo recognized (purportedly by dropping objects off the Tower of Pisa) that all objects fall with the same acceleration. A more massive object needs a greater force to achieve the same acceleration in direct proportion to its mass (Newton's second law, or $F = ma$). Therefore, the property that determines the gravitational force on an object (its "gravitational mass") is the same as the property that determines how hard it is to accelerate ("inertial mass"). Gravity and acceleration are related.

Therefore, the property that determines the gravitational force on an object (its "gravitational mass") is the same as the property that determines how hard it is to accelerate ("inertial mass"). Gravity and acceleration are related.

The effects of Newtonian gravity and acceleration are indistinguishable. This is what makes general relativity a theory of gravity; any attempt to deal with accelerated reference frames brings in the indistinguishable effects of gravity. In 1907, Einstein asserted that in a small freely falling reference frame, gravity is not evident. Imagine you're in an elevator with its cable broken; if you take a ball out of your pocket and release it, it falls with the same acceleration you

do—and thus appears weightless. It is impossible to distinguish free fall in the presence of gravity from the complete absence of gravity. The elevator occupant is unfortunate because free fall will soon stop, but an astronaut in a space shuttle is in exactly the same situation—free fall—and, therefore, doesn't feel gravity.

Objects in a small, freely falling reference frame (for example, inside an orbiting spacecraft) behave just as they would if they were in a uniformly moving frame far from any source of gravity. Thus, special relativity applies in freely falling reference frames. In fact, such frames are the closest we can come to the ideal uniformly moving frames of special relativity. Accelerated motion in the absence of gravity is indistinguishable from unaccelerated motion in the presence of gravity.

Gravity in the general theory of relativity. In the general theory, laws of physics should be the same in *all* reference frames. Therefore, something

that is present in one reference frame but not in another can't be "real." Gravity can be "transformed away" by going into a freely falling reference frame. Therefore, what we usually think of as "gravity" or "the gravitational force" can't be what gravity really is.

What can't be transformed away are so-called "tidal forces," which in Newton's theory, result from *differences* in gravity from place to place. In a small reference frame, we won't notice the effects. In a large enough reference frame, even in free fall, these differences will be evident. Tidal forces are the "true" manifestation of gravity; however, because there is no underlying Newtonian gravity of which tidal forces are the differences, there must be some other explanation for gravity.

In 1912, Einstein argued that spacetime is *curved*, and gravity (e.g., what a Newtonian would call tidal force) is synonymous with the curvature of spacetime. Einstein's law of motion states that absent any force, an object moves in the straightest possible path in curved spacetime. *Locally*, that path is always a straight line at uniform speed, but on larger scales it reflects the geometry of spacetime—which is different from the Euclidean geometry studied in tenth grade. For example, parallel lines intersect in a spacetime with positive curvature. It is hard to picture spacetime curvature in four dimensions (three of space, one of time).

In summary, gravity is synonymous with the curvature of spacetime. Matter gets its "marching orders" (Taylor and Wheeler) *locally*, responding to the geometry of spacetime in its immediate vicinity. At the scale of a single particle, spacetime always looks locally flat and the particle acts as if it is in a uniformly moving reference frame. Special relativity applies perfectly. For extended objects or several spatially separated particles, the curvature of spacetime manifests itself in the subtle effects that used to be called "tidal forces." Gone completely is Newton's view of gravity as a force exerted between distant objects; in fact, gravity isn't a force at all, and free fall becomes the natural state of motion. The next logical question (to be answered in the next lecture) is: What makes spacetime curved? ■

Essential Reading

Chaisson, *Relatively Speaking*, Chapter 6.

Hey and Walters, *Einstein's Mirror*, Chapter 8.

Hoffman, *Relativity and Its Roots*, Chapter 6.

Mook and Vargish, *Inside Relativity*, Chapter 5, Sections 1–8.

Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy*, Chapter 5, from p. 93.

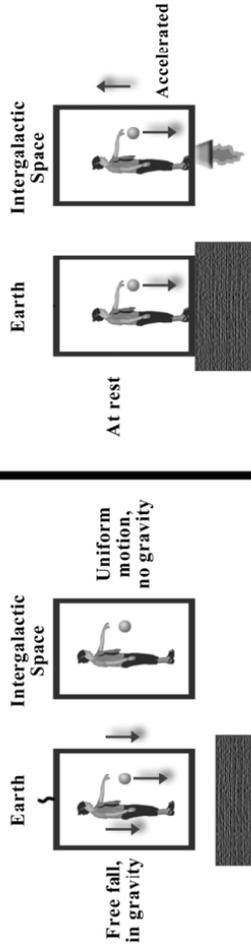
Suggested Reading

Taylor and Wheeler, *Spacetime Physics*, Chapter 9.

Questions to Consider

1. You drop a large rock and a small rock. Because of its larger mass, the gravitational force on the larger rock is greater. Why doesn't the larger rock fall with greater acceleration?
2. An airplane flying from San Francisco to Tokyo first heads north toward the coast of Alaska. Why? How is this analogous to what happens in general relativity's description of gravity?

The Principle of Equivalence



The Principle of Equivalence states that there is no difference between being in a freefall toward Earth under the influence of gravity and being in uniform motion in intergalactic space far from any gravitational influence. If you were in a closed box with no windows, there is no way you could tell the difference between the two states.

The Principle of Equivalence states that there is no difference between being in a state of rest on Earth and accelerating at 1 g in intergalactic space. If you were in a closed box without any windows, there is no way you could tell the difference between the two states.

Tidal Forces



In this diagram, we see the effects of "tidal forces" upon objects. In this case, a laboratory that is a substantial fraction of the size of the Earth is descending toward the planet. Inside this hypothetical laboratory is a very large person and two balls that are a good distance away from each other. Because the force of the Earth's gravity points toward the center of the Earth, the balls will move together as they fall closer to Earth. Notice that the person and the laboratory are also affected by the non-uniform gravity. They are stretched lengthwise and is squashed horizontally.

Curved Spacetime

Lecture 14

It took Einstein nine years after the special theory of relativity to develop the general theory. It took him about six weeks of actually working to develop the special theory. So this is quite a change. And the reason it took so long is, as you can see, from the idea of curved spacetime, general relativity is a conceptually very difficult idea, compared with special relativity in many ways.

Gravity is synonymous with spacetime curvature, but what causes spacetime to curve? Einstein gave the answer: Matter and energy curve spacetime in their vicinity. In 1914, Einstein published his complete and fully quantitative theory. This is one of the crowning achievements of the human mind, because there was no experimental confirmation at the time that he developed the theory. The essence of general relativity consists of two simple statements:

- Matter and energy cause spacetime to curve.
- In the absence of forces, objects move in the straightest possible paths (*geodesics*) in curved spacetime.

We can use a simple analogy to demonstrate spacetime: Stretch a sheet of clear plastic and roll a small ball across it. With the sheet stretched flat (no curvature), the ball rolls in a straight line. A larger ball resting on the sheet distorts it; now the small ball's path is no longer straight because of the curvature of the sheet.

General relativity makes definite predictions that can be verified through observations. Where gravity is relatively weak, as in our solar system, the predictions of general relativity differ only slightly from those of Newtonian gravitational theory. But modern astrophysics offers examples in which general relativistic effects are dramatic. Elliptical orbits should not remain fixed in space but should rotate slowly about the gravitating body.

In our solar system, the planet Mercury shows the greatest effect, because it is closest to the Sun, but even here the effect is only about 1/100 of a degree of angle every century. Einstein knew of this subtle deviation from Newtonian gravitation and was delighted when his new general relativity could account for it. Today we know of collapsed stars in such close orbits that this *precession* effect is much more obvious. A famous case is the binary pulsar discovered in the 1970s and studied ever since by Joseph Taylor and Russell Hulse, who won the 1993 Nobel Prize for this work. This system includes a *neutron star*—an object with the mass of an entire star compressed into the size of a city—in orbit around another collapsed star. The neutron star spins rapidly and in the process emits regularly spaced radio signals, like a ticking clock. Studying these signals reveals orbital details, including the precession effect.

Time should run more slowly in regions where gravity (i.e., spacetime curvature) is stronger. A simplified explanation is that light loses energy “climbing” away from a gravitating mass. Light can’t slow down, but the frequency of the light waves is reduced. To an observer looking toward a region of strong gravity, the effect is to see time running slower in that region. This is called *gravitational time dilation*. In a very sensitive experiment at Harvard in 1960, physicists used nuclear radiation to verify gravitational time dilation, effectively measuring differences in the rate of time over a distance of a mere 74 vertical feet.

Gravitational time dilation is also verified by sensitive measurements of the frequency of radiation emitted by the Sun. The effect is much more obvious in collapsed stars, in which the dense concentration of matter results in much greater curving of spacetime. Such stars include *white dwarfs*, which have the mass of the Sun crammed into the size of the Earth, and the neutron stars described above. Gravitational time dilation is also important in the round-the-world atomic clock experiment described in Lecture 9. Even though curvature of spacetime in Earth’s vicinity is slight, the Global Positioning System (GPS)

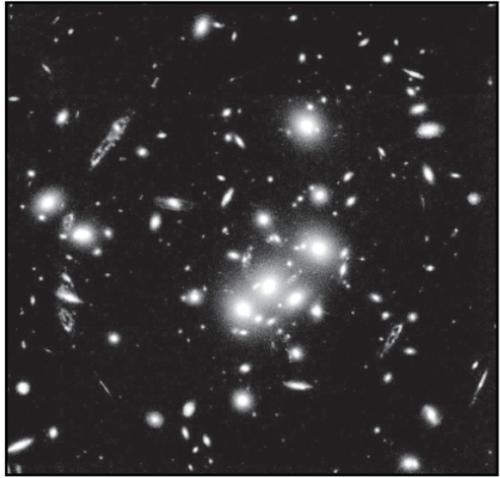
Time should run slower in regions where gravity (i.e., spacetime curvature) is stronger. A simplified explanation is that light loses energy “climbing” away from a gravitating mass.

is so precise that its position determinations would be off by a significant fraction of a mile if gravitational time dilation were not taken into account.

Light travels in the straightest possible path, but in curved spacetime that path is not a straight line. General relativity predicts that light should be bent by gravity. The equivalence principle shows why this must be so. When starlight passes

by the Sun, its path is bent slightly, making the apparent positions of the stars change relative to their positions when the Sun is not near the light path. Observations of this can be made only during an eclipse of the Sun. This effect was first observed on May 29, 1919, by Sir Arthur Eddington. A Quaker, Eddington had been granted an exemption from service in World War I so he could undertake a test of Einstein's theory as soon as possible after the war ended. By happy coincidence, the first available eclipse was May 29, 1919—a date when there happened to be many bright stars near the Sun. Confirmation of Einstein's prediction catapulted Einstein to world fame.

Today, astronomers routinely observe distant objects whose light is bent significantly by massive galaxies. Called *gravitational lensing*, this effect can produce multiple images of a single object. Gravitational lensing is also used to search for dark, massive objects that might constitute the “missing mass” in the universe. When such an object passes in front of a star, its gravity momentarily focuses the star's light, producing a bright flash. This effect is called *microlensing*.



Gravitational lens.

W.N. Colley and E. Turner (Princeton University),
J.A. Tyson (Bell Labs, Lucent Technologies) and NASA.

General relativity predicts the existence of *gravitational waves*—“ripples” in the fabric of spacetime that travel at the speed of light. Gravitational waves should be produced in certain high-energy astrophysical situations, such as with dense objects in close orbits or the merging of black holes. Early attempts to detect gravitational waves involved huge aluminum bars that would vibrate in response to the waves. Gravity wave detectors that are currently in the design phase include space-based devices similar to the Michelson-Morley experiment, some with arms thousands of miles long. The binary pulsar, discussed above, should lose energy by radiating gravitational waves. The waves haven’t been detected directly, but changes in the orbit agree with general relativity’s prediction for the energy loss.

Finally, general relativity predicts the existence of *black holes*—a topic worthy of an entire lecture. Stay tuned! ■

Essential Reading

Chaisson, *Relatively Speaking*, Chapter 7.

Hey and Walters, *Einstein’s Mirror*, Chapter 9.

Will, *Was Einstein Right? Putting General Relativity to the Test*, Chapters 1–7.

Suggested Reading

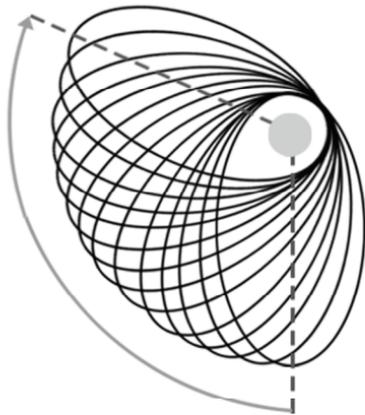
Wheeler, *A Journey into Gravity and Spacetime*.

Questions to Consider

1. In special relativity, we stressed that time dilation is reciprocal: When we’re moving relative to each other, I see your clock running slow, and you see mine running slow. Now we have gravitational time dilation in general relativity: If you’re closer to Earth or another gravitating body than I am, I see your clock running slow. Do you expect this effect to be reciprocal too, or will you see my clock running fast?

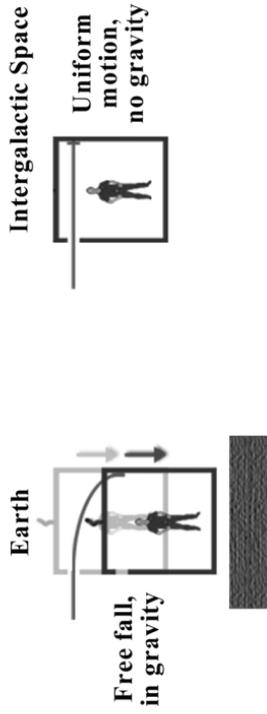
2. Gravity seems a pretty formidable force if you're trying to lift a heavy object or scale a cliff. In what sense, though, is gravity on Earth (and indeed throughout our solar system) weak?

Orbital Precession



Newtonian physics says that a planet's orbit should repeat exactly the same path forever. But general relativity predicts a gradual rotation, or **precession**, of the orbital axis. Within our solar system the effect is very small, but for the planet Mercury it *is* measurable.

Bending of Light



The right hand frame shows a small laboratory in intergalactic space, far from any gravitational influences. Furthermore, it's not accelerating. A beam of light enters the lab through a hole in one wall and strikes the wall directly opposite the hole.

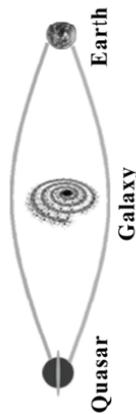
The left hand frame shows a similar small laboratory, now falling freely under the influence of Earth's gravity. The Principle of Equivalence asserts that the two situations are indistinguishable as far as the laws of physics are concerned. So a light beam that enters the hole in the side of the laboratory must strike the wall opposite where it entered. But the laboratory accelerates downward as the light moves across its interior, and therefore the light path must curve in order for the light to strike the wall opposite the hole. Thus the Principle of Equivalence shows that gravity must bend the path of a light beam.

Bending of Light

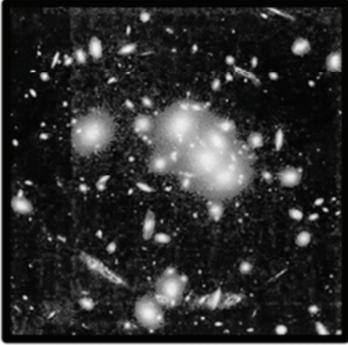


Light from a distant star (left) would normally take a straight-line path (faded line) to Earth. But in the case shown, the sun lies between the star and the Earth, and the Sun's gravity curves spacetime in its vicinity. The light follows the straightest possible path in this curved spacetime, and is thus bent around the Sun. An observer on Earth would have to look in different directions to see the star, depending on whether or not the Sun were between the Earth and the Star. Thus the apparent position of the star in the sky would differ in the two situations. With the Sun's relatively weak gravity, the change in observed star positions is very small, much smaller than the full bending around the Sun shown here.

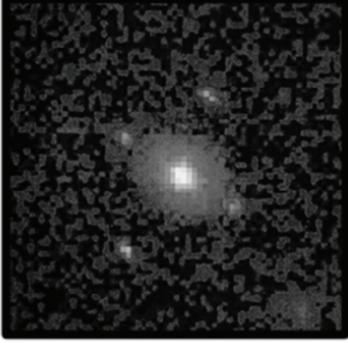
Bending of Light: A Gravitational Lens



Much more dramatic effects occur when a massive galaxy lies between the Earth and a distant quasar. The galaxy's curvature of Spacetime can create multiple paths for light from the quasar. This may result in multiple images of the same object, or in distortions where spacetime curvature has smeared the quasar's image into a series of arcs or even a complete ring. This phenomenon is known as **gravitational lensing**.



**A Gravitational
Lens as seen with the
Hubble Telescope**



**The "Einstein Cross"
as seen with the Hubble
Telescope**

Black Holes

Lecture 15

Throw the ball up, down it comes. Up, down it comes. Throw it a little faster. It goes up higher, stays there a little longer, but down it comes. Throw it faster still, it's up higher, stays longer, but back it comes. What goes up must come down, right? No.

The speed an object must have to escape forever from Earth or any other gravitating body is the *escape speed*. Escape speed for Earth is 7 miles per second, but it can be much higher for objects that are both massive and small, such as the white dwarfs and neutron stars that form at the ends of some stars' lifetimes. Escape speed provides a measure of how much the predictions of general relativity diverge from those of Newton's gravitation. In regions where escape speed is small compared with the speed of light (i.e., weak gravity), the two theories are in close agreement, and general relativistic effects are subtle. This is the case everywhere in our solar system. Where escape speed approaches the speed of light (i.e., strong gravity), only general relativity provides an accurate description of gravitational phenomena.

General relativity predicts the existence of *black holes*, objects whose escape speed exceeds that of light. Black holes require extreme concentrations of matter. To form a black hole from Earth, the planet would have to be compressed to a sphere about one inch in diameter. For the Sun to become a black hole, it would have to be squeezed from its current million-mile diameter to a diameter of about 4 miles.

Contrary to popular opinion, a black hole does not “suck in” everything in its vicinity.

Let's take a further look at black holes. Nothing that falls into a black hole can escape. The boundary of the region of no return is the hole's *event horizon*, where escape speed becomes c . Contrary to popular opinion, a black hole does not “suck in” everything in its vicinity. At significant distances from the hole, gravity behaves just as it would around any other gravitating object.

Gravitational time dilation becomes infinite at the event horizon—meaning an outside observer would never see an object actually cross the horizon. To a small-size observer falling into the hole, however, everything would seem perfectly normal. (Remember that free fall is the “natural state of motion” in general relativity.) However, the falling observer would experience destructive tidal forces either before or after reaching the horizon, depending on the size of the observer and the hole.

Do black holes exist? How can they be formed? Black holes may be formed in the intense *supernova* explosions that end the lifetimes of massive stars. These explosions leave a collapsed remnant that may be a neutron star or, if more massive than about three times the Sun’s mass, must become a black hole. Such stellar-mass black holes may form in binary star systems, in which case they can be detected by their effects on the companion star. Typically, gas flows from the companion to form a disk of gas orbiting the hole. The matter heats up through friction as it spirals toward the event horizon, emitting copious x-rays.

Supermassive black holes—with the mass of millions or billions of Suns—seem to lurk at the centers of most galaxies, including our Milky Way. The intense radiation emitted by matter falling into the hole early in a galaxy’s life may account for *quasars*, distant objects with colossal energy output. Galactic holes grow gradually as stars fall into them.

It is speculated that rotating black holes may be able to form *wormholes*, tunnels connecting remote parts of spacetime. ■

Essential Reading

Chaisson, *Relatively Speaking*, Part IV.

Suggested Reading

Kaku, *Hyperspace*, Chapters 10–11.

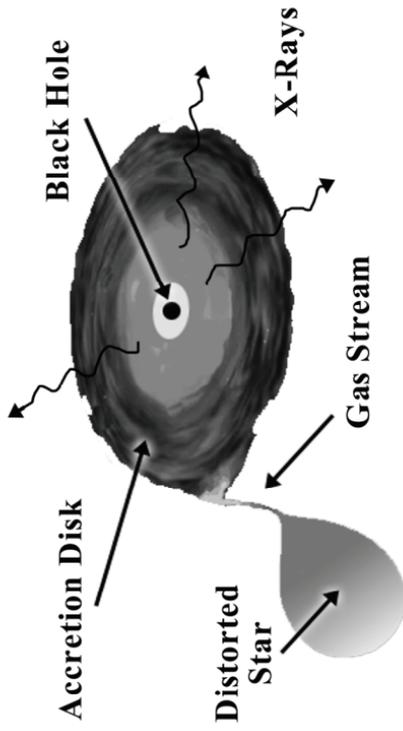
Lasota, “Unmasking Black Holes,” *Scientific American*, vol. 280, no. 5, pp. 40 (May 1999).

Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy*, Chapters 7–10.

Questions to Consider

1. If the Earth suddenly shrank to become a black hole, with no change in mass, what would happen to the moon in its circular orbit?
2. If you were falling into a black hole and looked at your watch, would you notice time “slowing down”? Justify your answer using basic principles of relativity.
3. For another fascinating look at black holes, wormholes, and spacetime, we recommend The Teaching Company course *Understanding the Universe: An Introduction to Astronomy, 2nd Edition* by Professor Alex Filippenko of the University of California at Berkeley.

Black Hole in a Binary Star System



Into the Heart of Matter

Lecture 16

We want to understand the rules of physics that govern the behavior of the universe at the sub-atomic and atomic scale. And those rules are bizarre, indeed. Those are the rules of quantum physics, or quantum mechanics.

We are headed into quantum physics, the implications of which are even stranger than those of relativity. Relativity asks that we alter our conceptions of space and time but with modified meanings, our common-sense language still applies. In quantum physics, though, our everyday language is completely inadequate to describe physical reality. The next lectures address quantum physics by:

- Examining the nature of matter through early 20th-century understanding of the atom and highlighting problems with atomic models based on classical physics.
- Resolving these problems with the idea of the *quantum*.
- Developing the ideas of *quantum physics*, which governs the behavior of matter and energy at the atomic scale.
- Resuming the descent toward the ultimate heart of matter, looking at elementary particle physics.
- Applying both subatomic physics and relativity to an understanding of the evolution of the universe.
- Describing attempts to merge relativity and quantum physics into a “Theory of Everything.”

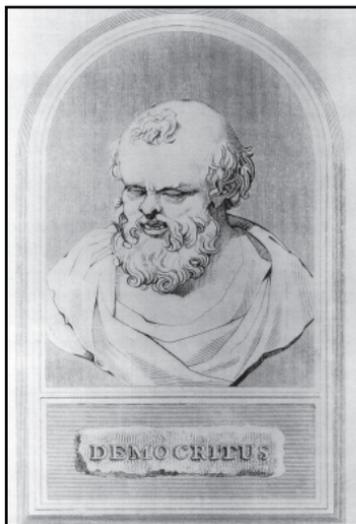
Democritus (c. 400 B.C.) proposed that matter consists of indivisible particles called *atoms* (the term itself means “indivisible”). John Dalton (early 1800s) organized elements by atomic weight and set forth the seeds

of modern atomic theory. Dmitri Mendeleev (1869) developed the periodic table of the elements based on an orderly, repeated arrangement of elements with similar chemical properties.

In the late 1800s, subatomic particles were discovered. Henri Becquerel discovered radioactivity and the Curies (Marie and Pierre) explored the new phenomenon. J. J. Thomson discovered the electron, which led to William Thomson (Baron Kelvin) proposing the “plum-pudding” model of the atom (1900), in which electrons are embedded in a “pudding” of positive charge. American Robert Millikan won the 1923 Nobel Prize in physics for his measurement of the charge of the electron.

In 1909–1911, Ernest Rutherford, Hans Geiger, and Marsden performed experiments in which they shot high-energy alpha particles from a radioactive substance toward a thin gold foil. Most went right through or were deflected slightly, but a few bounced back in the direction from which they had come. Rutherford interpreted this to mean that the atom is mostly empty space, with nearly all its mass concentrated in a tiny, positively charged nucleus. He proposed a “solar system” model for the atom, with electrons held in orbit around the nucleus by the attractive electric force.

These early models of the atom presented some problems. The first problem was that atoms shouldn't exist! Maxwell's equations of electromagnetism predict that accelerating electric charges should emit electromagnetic waves (light). The electrons in Rutherford's atom are accelerating, because they are moving in circles. They should lose energy by radiating electromagnetic waves. Then, like a satellite losing energy because of friction with Earth's upper atmosphere, they should spiral into the nucleus. All this should happen



Democritus.

in a split second! Even if Rutherford's atom didn't collapse, the solar system model offers no explanation of atomic spectra—the discrete colors of light emitted by atoms of each different element.

These early models of the atom presented some problems. The first problem was that atoms shouldn't exist!

Another problem related to classical physics (Maxwell's electromagnetism and thermodynamics) is the so-called *ultraviolet catastrophe*. Hot, glowing objects should give off electromagnetic waves (light), because of the vibrations of their constituent atoms participating in the microscopic energy we call heat. Indeed, hot objects do glow (picture a hot stove burner or the filament of a light bulb). Classical physics says that they should also give off an infinite amount of electromagnetic radiation, concentrated toward the shorter wavelengths (ultraviolet being the shortest wavelength of electromagnetic waves known at the time). Obviously, this doesn't happen. How can that be explained? ■

Essential Reading

Hey and Walters, *The Quantum Universe*, Chapter 4.

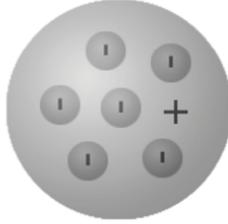
Wolf, *Taking the Quantum Leap*, Part I.

Questions to Consider

1. How did the rare occurrence of an alpha particle's being bounced back in the direction it came from imply that the mass of an atom is concentrated in a tiny volume?
2. How did the discovery of subatomic particles alter Democritus's original concept of the atom?

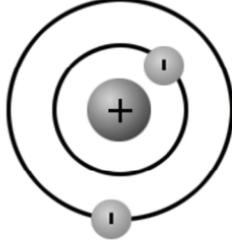
For additional coverage of the topic presented in this lecture, we recommend The Teaching Company course *The Joy of Science* by Professor Robert Hazen of George Mason University and the Carnegie Institution of Washington.

Atomic Models



Thompson/Kelvin (1900)
"Plum Pudding"

In 1900, Thompson and Kelvin hypothesized that the structure of the atom consisted of a fixed number of electrons, carrying "negative" charge, embedded in a mass that had an equal but opposite "positive" charge. Due to its structure, this model was called the "Plum Pudding" model of the atom.



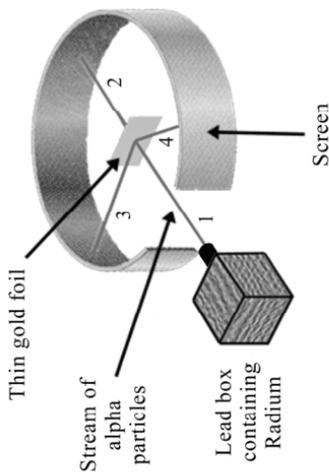
Rutherford (1911)
"Solar System"

Based on the results of his experiment, Rutherford devised another model of the structure of the atom in 1911. In this model, a central "nucleus" with a positive charge was surrounded by electrons with negative charges that circled the nucleus in orbits. Due to its parallels to the Sun and the planets, this model was called the "Solar System" model of the atom.

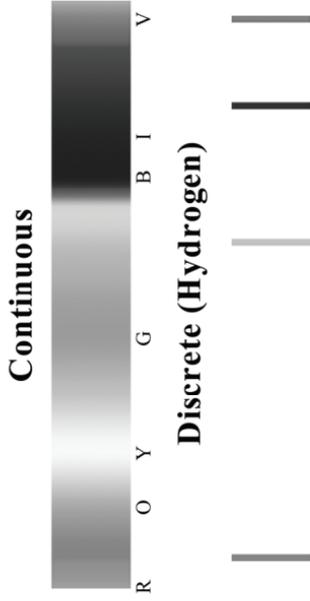
Rutherford's Experiment

In Ernest Rutherford's classic experiment, a lead box containing the radioactive element radium, was placed in front of an open cylindrical screen. As it decays the radium emits high-energy subatomic particles, called alpha particles (and now known to be helium nuclei). A small hole was cut into the side of the lead box that faced the screen allowing a stream of alpha particles (1) to shoot out toward the screen. In the center of this open screen, Rutherford suspended a sheet of gold foil which served as the target for the alpha particles.

Rutherford predicted that the alpha particles would shoot directly through the gold foil (2) and hit the opposite side of the screen, uninterrupted by the gold foil. And indeed, most of the alpha particles did just that. But to Rutherford's astonishment, a few (3 and 4) were deflected at large angles. This led Rutherford to postulate the existence of a tiny but massive atomic nucleus, and led to his "Solar System" model of the atom.



Atomic Spectra



This diagram shows the phenomenon of discrete emission in atomic spectra. The top band is a continuous spectrum of visible light from red to violet. The bottom band is the spectrum emitted by hydrogen atoms, consisting of discrete colors. Each element has a different pattern of these spectral lines.

Enter the Quantum

Lecture 17

Now, we're sitting at about the turn of the 20th century, plus or minus 10 years, depending on which phenomena we're talking about, and we know that there are atoms. Unlike Democritus suggested though, they're not indivisible.

Experiments beginning in the 1880s showed that light shining on a metal surface in vacuum can eject electrons from the metal. This is called the *photoelectric effect* and is the basis of an early kind of “electric eye” used in everything from automatic door openers to sensitive light measuring instruments. Classical physics attempts to explain the photoelectric effect. Electrons are jostled by the alternating electric field of the electromagnetic wave that is the light. They absorb energy from the wave, eventually gaining enough to escape the metal. Because the wave energy is spread over a wide area, it should take a long time for any one electron to be ejected. Therefore, there should be a delay between the light's striking the metal and electrons being ejected. The color of the light should not matter.

The experimental results are at odds with the classical predictions. Electrons are ejected as soon as the light shines on the metal. The color of the light does matter. If the light is too red, no electrons are ejected, no matter how bright the light. If the light is blue enough, electrons are ejected, and their energy increases as the color of the light moves toward violet and ultraviolet.

Let's quickly review the four problems faced by classical physics at the turn of the 20th century, in the order in which I've introduced them. First, there was the problem of the existence of atoms: Atoms shouldn't last. Second, there was the problem of the spectra of light that atoms emit. Atoms should emit light of all colors and not, as had actually been observed, discrete spectral lines unique to each element. The third problem was the ultraviolet catastrophe: Hot objects should glow with an infinite amount of ultraviolet light. And finally, there was the problem of the photoelectric effect: Electron ejection should take a long time and should be independent of color.

Now let's resolve the problems, here in historical order, although the first is the most obscure. Max Planck (1900) showed that the ultraviolet catastrophe could be resolved by assuming that atomic vibrations are *quantized*, occurring only in multiples of a certain basic amount. That required basic amount was given by the formula $E = hf$, where E is the energy of a vibrating atom, f is its frequency (how many vibrations per second), and h is a new constant of nature that became known as *Planck's constant*.

Einstein (1905, same year as special relativity!) explained the photoelectric effect by declaring that the energy in a light wave is not spread uniformly over the wave but is concentrated in particle-like “bundles” called *photons*. The energy of a photon is quantized: For light of frequency f , the energy E of a photon is given by $E = hf$, where again h is Planck's constant. Einstein's proposal explains the photoelectric effect because it takes a certain amount of energy to eject an electron from the metal. If light is too red (too low a frequency f), then the energy of its photons is lower than that required to eject electrons, and none will be ejected. Bluer light can eject electrons and, as the light frequency increases, the photons can impart more energy to the light. Ejection occurs immediately because the light energy is concentrated in photons, and an electron need be hit by only a single photon to be ejected.

Atoms radiate electromagnetic waves (light) only when electrons jump among orbits, emitting specific colors of light. This explains the spectra of atoms.

In 1913 Niels Bohr proposed the *Bohr model of the atom*. The Bohr model explained both the existence of atoms and their spectra but had no deeper theoretical basis. Atomic orbits are quantized, with only certain discrete orbits allowed. These orbits correspond to discrete values of the electrons' energy. Bohr's actual quantization condition is that the allowed angular momentum, L , of an orbiting electron (a measure of rotational motion) is given by $L = h/2p$, where p is the electron's momentum and h is again Planck's constant. Electrons in allowed orbits don't radiate electromagnetic waves; they don't crash into the nucleus, but rather stay in orbit. Atoms radiate electromagnetic waves (light) only when electrons jump among orbits, emitting specific colors of light. This explains the spectra of atoms.

Common to all these resolutions is *quantization* involving Planck’s constant h . Planck’s constant is a measure of the fundamental “graininess” of the universe at small scales. Planck’s constant is very small (about 10^{-33} , or $1/1,000,000,000,000,000,000,000,000,000,000,000,000,000,000$ in the standard meter-kilogram-second system of units). For that reason, the effect of quantization is noticeable only at the atomic scale and smaller. If Planck’s constant were truly zero, then the universe would be continuous and classical physics would hold. But h is not zero, and that makes all the difference. ■

Essential Reading

Gribben, *In Search of Schrödinger’s Cat*, Chapters 3–4.

Han, *The Probable Universe: An Owner’s Guide to Quantum Physics*, Chapters 1–3.

Wolf, *Taking the Quantum Leap*, Chapters 3–4.

Suggested Reading

Pagels, *The Cosmic Code*, Part I, Chapter 4.

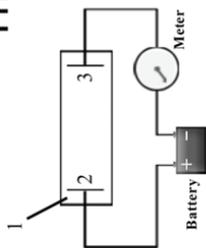
Spielberg and Anderson, *Seven Ideas that Shook the Universe*, Chapter 7, through Section D4.

Questions to Consider

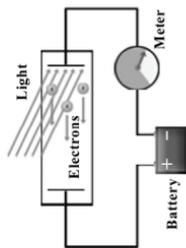
1. What do Bohr’s atomic model, Planck’s resolution of the ultraviolet catastrophe, and Einstein’s explanation of the photoelectric effect all have in common?
2. If quantization is such a basic feature of the universe, why don’t we notice it in our everyday lives?
3. Speculate on what life would be like in a universe in which Planck’s constant was much larger—so much larger that the minimum energy for

a photon of visible light was about the same as the energy of a tennis ball just after being served.

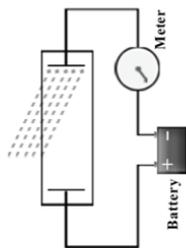
The Photoelectric Effect



This experiment consists of an evacuated glass tube (1) containing two metal electrodes (2 and 3). One electrode (2) is connected to the positive terminal of a battery. The other electrode (3) is connected to the negative terminal of the battery, by way of a meter. Because of the gap between the electrodes, no electric current can flow.



Light incident on the metal electrode may cause electrons to be ejected. The electrons are then attracted to the positive electrode giving rise to an electric current. The meter registers this current.



If the frequency of the light is too low (too long a wavelength, or of a color toward the red end of the spectrum), then no electrons are ejected, no matter how intense the light is.

Wave or Particle?

Lecture 18

Light has, at least, some aspects of particle-ness. It comes in these little, discrete bundles that act pretty much like particles. They hit an electron, and they bounce it out of the metal. So, which is it—wave or particle?

Newton (in the mid-1600s) proposed that light consists of particles. He was able to explain the phenomena of reflection, refraction, and color using his particle model. Christian Huygens (1600) proposed an alternative: that light consists of waves. Thomas Young (1800) provided conclusive evidence that light is a wave. His double-slit experiment showed that light beams interfere, something that is possible only with waves. Maxwell in the 1860s stated that light was a wave. Einstein (in 1905) explained the photoelectric effect by proposing that light behaves as if it were a particle, in that light energy is concentrated in particle-like photons.

The *Compton effect* (1923) showed what happens when light (in this case, x-rays) interacts with electrons. Historically, the Compton effect was for many old-time physicists the final convincing evidence for the reality of quanta. Classical physics predicts that the electron should absorb energy from the light wave, then re-emit at the same frequency. Experiments show that the light scatters off the electron with lower frequency—just as if the light



Thomas Young.

were a beam of particles that interacts with electrons in the same way that two billiard balls collide. An incoming photon bounces off an electron, giving up some of its energy and lowering its frequency (since $E = hf$).

This presents a quantum quandary. If light consists of particles, how can we explain the results of two-slit interference experiments? Try to look at the process in more detail:

- Which slit does a photon go through? Try to find out by covering up one slit—and the interference pattern disappears! How did the photons going through the other slit “know” about the first slit being closed?
- Try putting photon detectors at each slit, to “catch” photons in the act of going through. Again, the interference pattern disappears.
- Dim the light so that only one photon is present at a time. Still, an interference pattern gradually builds up. Somehow, each photon must “know” about both slits.

So is light a wave or a particle? The quantum answer: It’s both! If you don’t try to detect it, light acts like a wave and exhibits interference effects. The behavior of the waves is governed by Maxwell’s equations. A wave is a spread-out thing, and it can “sample” both slits. Thus, one way to answer the question of which slit the photon went through is to say that it went through both. Close one slit, and the wave can’t interfere with itself on the other side, so the interference pattern disappears. If you detect light, it behaves

as if it consists of particles (e.g., ejection of an electron in a light detector, darkening of a grain on photographic film, and so on).

So is light a wave or a particle? The quantum answer: It’s both!

There is a relation between wave and particle, but it is only a statistical one. The *probability* of finding a photon is related to

the wave amplitude; the stronger the wave is at some point, the more likely you are to find a photon there. Thus, the wave picture predicts that waves should be strong at certain points on the screen in a two-slit experiment, and quantum physics predicts that’s where you are most likely to detect photons.

The *wave/particle duality* at first seems to be a contradiction. How can light be both particle and wave? There's no contradiction, according to Bohr's *Principle of Complementarity*. Rather, wave and particle aspects of light are complementary. Both are needed for a full description of the behavior of light. The two aspects cannot manifest themselves together at the same time. If you do an experiment that involves wave aspects of light (e.g., an interference experiment), you'll find that light acts as if it were a wave. If you do an experiment that involves particle aspects (e.g., a photoelectric experiment), you'll find that light acts as if it were a particle.

Is quantum physics absurd? You may think so, but keep in mind that the theory has been remarkably successful in describing the world at the atomic and subatomic levels. Even some of the pioneers of quantum physics had similar doubts. ■

Essential Reading

Gribben, *In Search of Schrödinger's Cat*, Chapter 5.

Hey and Walters, *The Quantum Universe*, Chapter 1.

Wolf, *Taking the Quantum Leap*, Chapter 8.

Suggested Reading

Lightman, *Great Ideas in Physics*, Chapter 4, through p. 210.

Lindley, *Where Does the Weirdness Go?*, "Act I," pp. 3–86.

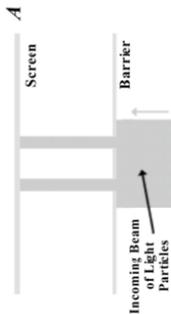
Pagels, *The Cosmic Code*, Part I, Chapter 5.

Questions to Consider

1. You cover first one slit, then the other, in a double-slit apparatus; in each case, you record the pattern that appears on the screen. If you then open both slits, will the resulting pattern be the sum of the patterns you see with only one slit open? Explain.

2. A friend who knows nothing about physics asks you whether light is a wave or a particle. How do you answer?

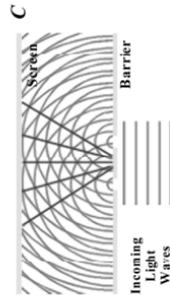
Wave Interference



The two-slit system is an experiment designed to determine the nature of light. If light were a particle, it would act as it does in **A**. Here, an incoming beam of light particles strikes a barrier with two slits in it. Only those particles that exactly lined up with the slits would pass through the barrier and would then strike the screen at two places directly opposite the slits.



If light were a wave, it would act as it does in diagrams **B** and **C**. In **B**, we show only the light passing through the left slit. The light wave hits the barrier and spreads through the left slit in concentric circles.



In **C** we see the light waves pass through both slits and interfere with each other. The thick lines mark regions of constructive interference, where wave crests meet crests and troughs meet troughs. Bright bands appear where these lines meet the screen.

Strangely, light has both wave and particle aspects. If we cover up one of the slits in the system, light acts as it does in diagram **A**. The light passes through the slit and hits the area of the screen directly opposite it. But when both slits are open, light acts as it does in diagrams **B** and **C**, forming an interference pattern.

Quantum Uncertainty—Farewell to Determinism

Lecture 19

Well, it's farewell to determinism and farewell to the clockwork universe once we have Heisenberg's uncertainty principle in place because quantum mechanics is going to eliminate forever the possibility that we live in a completely deterministic universe in which everything is predictable. Why is that? The fundamental reason is the reason of quantization.

Quantization means that we cannot observe the universe without affecting it. This, in turn, limits our ability to make measurements with arbitrary precision. Thus, we must say farewell to the “clockwork universe” of Lecture 3. The least obtrusive way to observe something is to see it—that is, to bounce light off it. First, we will consider how to prepare the light.

Recall that the probability of finding a photon is proportional to the intensity of the associated light wave at that point. If we want to know with precision where a photon is likely to be, then we need a *wave packet*, with the “wiggles” of the wave confined to a small region. We can do this by producing, for example, a very short pulse of laser light. But note that making a localized wave such as this requires a short wavelength and, correspondingly, a high frequency.

Heisenberg's quantum microscope “thought experiment” explores an attempt to measure simultaneously the position and velocity of an electron with high precision, by bouncing light (i.e., minimum one photon) off the electron. To get accurate position information, we need a localized photon. There's a problem, though: The localized photon has high frequency and, therefore, high energy (recall the quantization condition $E = hf$). As it bounces off the electron, the photon transfers a lot of energy to the electron, altering its velocity substantially. The observation destroys some of the information—the velocity—that we sought to measure.

Note the crucial role of quantization here: The requirement for a *minimum* amount of light energy—one photon’s worth—causes the problem. We can’t observe a system without interacting with it, and when energy is quantized, that means disturbing the system. Surely there’s a way out of this problem: We can make the photon energy lower, thus reducing the disturbance. But lower photon energy means lower frequency (again, $E = hf$), longer wavelength—and a less localized photon. Now our measurement of the electron’s position is less precise. The quantum microscope thought experiment reveals a tradeoff between our ability to measure a particle’s position and its velocity simultaneously. If you make the velocity measurement more precise, you lose information about position and vice versa.

The *Heisenberg uncertainty principle* is the formal statement of this tradeoff. The uncertainty principle states that it is impossible to measure simultaneously and with arbitrarily high precision both a particle’s position and its velocity (actually its momentum, the product of mass and velocity). Quantitatively, the uncertainty principle says that the product of a particle’s mass, the uncertainty in its position, and the uncertainty in its velocity cannot be less than Planck’s constant h : $m \Delta x \Delta v > h$. Because h is so small, the uncertainty principle has a negligible effect on measurements of normal-sized objects, such as planets, baseballs, and even bacteria. At the atomic scale, however, where particle masses are tiny, the uncertainty principle severely limits our simultaneous knowledge of particles’ positions and velocities.

What does it mean? Let’s consider the philosophical interpretation and implication. Most physicists subscribe to the *Copenhagen interpretation* of quantum physics. This view grows out of logical positivism, with its claim that it makes no sense to talk about what cannot be measured. In the Copenhagen interpretation, not only can one never measure the velocity and

The uncertainty principle states that it is impossible to measure simultaneously and with arbitrarily high precision both a particle’s position and its velocity (actually its momentum, the product of mass and velocity).

position of a particle simultaneously, but it also makes no sense to say that the particle *has* a velocity and a position.

Under the Copenhagen interpretation, such particles as electrons and protons simply can't be thought of as miniature bowling balls, whizzing around in precise orbits. Rather, they're fuzzy, statistical things describing paths that are only vaguely determined. Because precise velocity and position are required to use Newton's laws to predict future motion, the uncertainty principle and the Copenhagen interpretation abolish the strict determinism of the Newtonian "clockwork universe."

Not all physicists accept the Copenhagen interpretation. For all his life, Einstein was among its staunchest critics. His famous remark, loosely paraphrased "God does not play dice with the universe," expresses his rejection of quantum indeterminism. (Einstein's actual words are "But that He [God] would choose to play dice with the world...is something that I cannot believe for a single moment.") Today, a small group of physicists is pursuing alternatives to the Copenhagen interpretation. Among these are *hidden variable theories* that posit an underlying deterministic reality hidden from our measurement by the uncertainty principle. However, recent experiments, to be described in Lecture 21, place severe constraints on such theories. ■

Essential Reading

Hey and Walters, *The Quantum Universe*, Chapter 2.

Wolf, *Taking the Quantum Leap*, Chapter 7.

Suggested Reading

Lindley, *Where Does the Weirdness Go?*, "Intermission," pp. 87–121.

Pagels, *The Cosmic Code*, Chapters 9–10.

Questions to Consider

1. Why can't we get around the uncertainty principle by observing the electron first with a high-energy, localized photon to get its position, then with a low-energy, spread-out photon to get its speed?
2. The statistical nature of quantum physics is often cited to explain the possibility of our having free will and has also been used by some in attempts to explain consciousness. What bearing do you think quantum physics has on free will and consciousness?

Wave Packets



Broad

- Photon not localized
- Long wavelength
- Low frequency



Narrow

- Photon well localized
- Short wavelength
- High frequency

Heisenberg's "Quantum Microscope"



Heisenberg devised this thought experiment to show how interactions between an observer and the system under observation result in unavoidable and unpredictable disturbances in the system—a phenomenon that underlies Heisenberg's uncertainty principle. The experiment attempts to measure the position and velocity of an electron by shining light on it and detecting the scattered light. But light has both a wave and a particle nature, and to know precisely where the light is we need a "wave packet" of short-wavelength light (A. above). Using such a packet, we can determine the electron's position to high precision. But a short wavelength corresponds to a high frequency and, by the quantization equation $E=hf$, to a high energy for the light photons. High-energy photons scattering off the electron impart momentum to it in an unpredictable way, thus disturbing its velocity. So this experiment measures the electron's position precisely, but provides little information about its velocity.



To get around the problem of high-energy photons disturbing the electron's velocity, we try instead to use low-energy photons. But these correspond to low frequency and thus long wavelength—and long wavelength "wave packets" aren't precisely localized. Thus the experiment measures the electron's velocity with precision, but its position remains uncertain. It's impossible to measure simultaneously both position and velocity with arbitrary precision. The standard interpretation of quantum physics goes further to say that it is meaningless to talk about a subatomic particle's having simultaneously both a well-defined velocity and a well-defined position.

Particle or Wave?

Lecture 20

“Particle or Wave?” Did I say that right? Didn’t I have a title just like that before? Well, if you think about Lecture 18, the title was “Wave or Particle?” This one’s very, very similar, for reasons that will soon become obvious.

Lecture 18 showed that light has a dual nature; it is both wave and particle. In 1923, the French prince Louis de Broglie (pronounced “de Broy”) put forth, in his doctoral dissertation, a remarkable idea: If light exhibits both wave and particle behavior, why not matter as well? Then, there should be “matter waves” associated with material particles.

De Broglie proposed that the wavelength of a matter particle’s associated wave depends on the particle’s mass and velocity: $wavelength = h/mv$. Because h is tiny, so is the matter wavelength, especially for normal-sized objects such as planets, people, baseballs, and bacteria, whose mass m is also substantial. With the wavelength much less than the size of the object or the systems with which it interacts, we don’t notice the wave aspect of ordinary matter. For subatomic particles, though, the mass m is small and, therefore, a particle’s wavelength can be comparable to the size of the systems with which it interacts. In particular, the wavelengths of atomic electrons are comparable to the sizes of atoms. Because wavelength also depends on velocity, it can become significant, even in macroscopic systems, when particle velocities become very small—something that happens only at temperatures close to absolute zero.

Because wavelength also depends on velocity, it can become significant, even in macroscopic systems, when particle velocities become very small—something that happens only at temperatures close to absolute zero.

De Broglie's matter-wave hypothesis has been verified in experiments involving electron beams similar to the double-slit experiment of Lecture 18. In practice, the closely spaced atoms of a crystal serve as the slit system, and the electrons exhibit the same interference effects as the photons in an optical double slit. Which slit did the electrons go through? The answer is the same as in Lecture 18. When we're not trying to detect it, the electron acts as a wave and "samples" both slits.

We have seen how quantum physics describes the behavior of light. Light waves (electromagnetic waves) are governed by Maxwell's equations of electromagnetism. In classical physics, the solutions to those equations describe the electromagnetic waves, and that's the end of it. In quantum physics, the solutions to Maxwell's equations describe waves that give the *probability* of detecting photons. The link between the wave equation and the particles is a statistical one.

The quantum description of matter is similar. For each particle, there is a *wave equation*, which in nonrelativistic quantum physics is the *Schrödinger equation* first proposed by Erwin Schrödinger in 1926. The solutions to this equation don't directly describe actual events. Instead, they give the probability that the associated particle will be found at a given place and time.

Matter waves explain Bohr's atomic theory. The allowed electron orbits are those in which a *standing wave* can fit—just as the notes played by a violin string are those that can fit on the string. Because wavelength is related to frequency and, thus, to energy ($E = hf$), the atomic energy levels are quantized. So are energy levels in any confined system.

Waves are continuous, spread-out entities—and here "waves" includes the solutions to the Schrödinger equation that describe the behavior of matter particles. This leads to unusual new phenomena, such as quantum tunneling, wherein a particle "tunnels" through a barrier from which classical physics says it doesn't have enough energy to escape. Does it really occur? Yes, radioactive particles appear outside atomic nuclei from which classical physics says they do not have the energy to escape. In another example, hydrogen nuclei in the Sun's core overcome the "barrier" of electrical

repulsion when classical physics says they can't. They fuse to make helium—and in the process, release the energy that keeps us alive! Increasingly, microelectronic devices make use of quantum tunneling, including devices that may be at the heart of computers thousands of times faster than those we have now.

A long, continuous wave has a well-defined wavelength, hence velocity by de Broglie's relation $wavelength = h/mv$. But the associated particle can be found anywhere, so the position is completely uncertain. A short, localized wave is built up of lots of different wavelengths. You know where the associated particle is, but its wavelength and velocity are very uncertain. The uncertainty principle and wave-particle duality are inherent features of nature. There is no way around them.

Nevertheless, quantum physics does make some exact predictions. For example, it predicts precisely the energy levels of atomic electrons. The atomic spectra predicted from these energy levels agree precisely with experimental measurements. What quantum physics can't predict is the precise path and behavior of individual particles. ■

Essential Reading

Hey and Walters, *The Quantum Universe*, Chapter 3.

Wolf, *Taking the Quantum Leap*, Chapter 5.

Suggested Reading

Lightman, *Great Ideas in Physics*, Chapter 4, from p. 210.

Questions to Consider

1. Whenever a particle is held in a confined space, as between rigid walls or by the electric force in an atom, its energy levels are quantized. Use de Broglie's matter-wave hypothesis to explain how this energy quantization arises.

2. Planck's constant can be expressed as $h = 10^{-33}$ in the standard meter-kilogram-second system of units. The mass of an electron is about 10^{-30} kilograms, and an atom is about 10^{-10} m in diameter. Use de Broglie's formula $wavelength = h/mv$ to estimate the wavelength of an electron moving at 10^6 meters per second and compare with the size of an atom. Repeat for a baseball (mass 0.1 kilograms) moving at 10 meters per second and compare with the size of the baseball. Your answers will show why the wave nature of matter is crucial at the atomic scale but completely irrelevant on the scale of everyday objects.

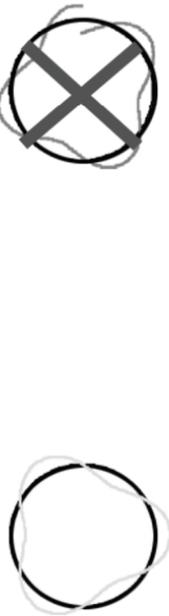
Standing Waves

On Strings...



This diagram shows a string fastened at both ends to rigid supports; an example would be a violin or piano string. The string can be set into vibration, but because the ends are fixed the only vibrations it can sustain are those wave patterns have fixed points the same distance apart as the ends of the string. At the left is one such vibration; for this case two full wavelengths fit between the ends. At right is a vibration that is not allowed, because at the right-hand support the wave is not at a fixed point. In a stringed musical instrument, the allowed vibration frequencies determine the notes that can be played.

In Atomic Orbits...



A similar effect occurs in atomic electron orbits, where the wave function for the electron must fit around the orbit. An allowed orbit is shown at left; a disallowed orbit on the right. The allowed orbits correspond to the discrete energy levels of atomic electrons.

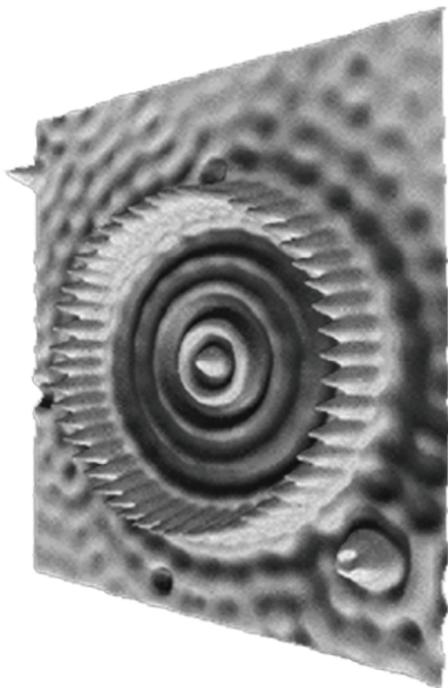
Quantum Tunneling



This diagram illustrates quantum tunneling, a remarkable phenomenon that becomes evident on subatomic scales. The sequence above shows a particle trapped between two barriers. Classical physics asserts that the particle can move back and forth and might be found anywhere between the barriers, but that it will never be found beyond the barriers.



In quantum physics, however, a particle is not localized precisely. Instead, the probability of finding the particle at a certain place depends on the size (amplitude) of the wave function at that point. The mathematical description of the wave function requires it to have nonzero amplitude outside the barriers. As suggested by the amplitude of the wave function shown here, the particle is most likely to be found between the barriers (left frame). But there's a small probability that it will be found outside (right frame)—having “tunneled” through the barrier. Such quantum tunneling plays an important role in many phenomena, including electronic devices and the nuclear processes that keep the Sun shining.



A Quantum Corral

Courtesy of
IBM Corporation, Research Division
Almaden Research Center

Matter Waves and Uncertainty

Continuous Wave:

Wavelength, hence velocity, precisely known.
Position completely uncertain.



Wave Packet:

Position well known.
Wavelength, hence velocity, uncertain.



Quantum Weirdness and Schrödinger's Cat

Lecture 21

This lecture, which is new to this version of the course, is a digression into a couple of topics that are of considerable interest in the popular study of quantum physics. They are also matters of debate among philosophers and physicists who are interested in the interpretation of quantum physics.

We've seen that electrons or photons in a double-slit experiment act as waves. In a sense, an electron can be said to pass through both slits. More precisely, until we detect the electron, quantum physics says it's in a *superposition state*, neither here (slit 1, say) nor there (slit 2) but with a probability of being found here and a probability of being found there. The existence of superposition states is an inherent result of the wave-particle duality, because it is the wave behavior of an unobserved particle that makes the ambiguity of superposition possible.

Measurement of position, velocity, or another property of a particle in a superposition state always gives a definite value. At the instant of measurement, the superposition ceases to exist and the particle is instead in a definite state. This is called the *collapse of the wave function* and represents an inherent involvement of the measuring apparatus and/or observer in the system under observation. In quantum physics, unlike classical physics, observer and observed are inextricably intertwined.

Quantum superposition is a real phenomenon, and recent experiments have succeeded in creating an atom that is in two places at once—i.e., in a superposition of “here” and “there.”

Quantum superposition is a real phenomenon, and recent experiments have succeeded in creating an atom that is in two places at once—i.e., in a superposition of “here” and “there.”

Can quantum superposition affect the everyday world? To show how it might, Schrödinger devised his famous cat example. Place a cat in a closed box that also contains a quantum system, in this case a radioactive atom that has a 50% chance of decaying each hour. The decay of the atom is a random event; quantum physics can predict only the probability of decay. Also in the box is a geiger counter that senses the decay of the radioactive atom. The geiger counter is connected to a diabolical apparatus that disperses poison into the cage when the counter detects the decay.

After the cat has been in the box for an hour, is it dead or alive? According to the Copenhagen interpretation, a quantum system is in a superposition state until a measurement forces the collapse of the wave function. Until we look in the box, the cat is in a superposition of dead and alive! Doesn't the geiger counter constitute a measuring system, collapsing the wave function at the instant it detects a decay? The answer is yes only in classical physics, where the measuring system can be considered distinct from what it is measuring. In quantum physics, we must consider the quantum state of the measuring apparatus as well. According to the Copenhagen interpretation, the box and its entire contents are in a superposition until we look in the box.

The many-worlds interpretation says that the universe splits. In one universe, the cat is alive; in the other, it's dead. The quantum state of a macroscopic object such as a cat or a geiger counter is more complicated than that of a single atom. The behavior of its individual atoms is not coherent or coordinated, and the entire cat remains in a superposition state for only an infinitesimal time. After that, it's really alive or dead, and we just don't know it. There is still much to learn about the boundary between quantum and classical systems.

In 1935, Einstein, Podolsky, and Rosen proposed a "thought experiment" that they felt revealed an underlying, objective reality independent of measurement. This is termed the EPR experiment from the initials of their last names. A simple example of an EPR experiment involves a particle that decays into a pair of electrons (not EPR's original example, but easier to grasp). The electrons fly apart in opposite directions. Electrons have *spin*, a microscopic, quantum version of *the angular momentum* of a spinning top or wheel or planet. Spin has two possible directions: "up" and "down" or "left"

and “right” or, generally, opposite directions along any line you care to test it on. Angular momentum is conserved, and the original particle has none. So the two electrons have opposite spins. Therefore, if you measure the spin of one electron, you immediately know the spin of the other—even though it’s far away and you haven’t interacted with it!

EPR claimed that the fact that the state of the second electron could be determined without interacting with it meant that its spin had an objective reality regardless of measurement. Spins of the two electrons are determined together, at the moment they are created. Otherwise, the result of the measurement on the first electron would have to be communicated instantaneously to the second—something Einstein called “spooky action at a distance” and that appears to violate special relativity. Bohr said no. The uncertainty principle still holds for the second electron as well, so EPR does not prove that quantities exist independent of measurement. Copenhagen rules quantum physics!

John Bell (1964) considered an experiment in which the electrons are tested again after a first spin measurement. He showed that the statistical distribution of the results would be different depending on whether the states of the electrons were really determined when they were created or were truly indeterminate until measured. EPR experiments done in 1982 by Alain Aspect of the University of Paris yielded statistics confirming quantum indeterminacy. Since then, ever more sophisticated experiments—including some in which the measuring apparatus is switched randomly after the particles are created—have confirmed that quantum indeterminacy is an inherent feature of EPR-type phenomena. By the late 1990s, experiments in Switzerland had confirmed the EPR effect in particles separated by several miles.

What does it mean? There is a strange “quantum connectedness” between the two particles in an EPR experiment. Somehow each “knows” what’s happening with the other. Quantum physics is an inherently *nonlocal* theory; particles in different places can be “entangled” in a way that precludes a strictly local description of each. However, this “spooky action at a distance” (in Einstein’s memorable phrase) does not violate relativity because it is impossible to use the effect to send information. ■

Essential Reading

Gribbin, *In Search of Schrödinger's Cat*, Chapters 8–11.

Lindley, *Where Does the Weirdness Go?*, pp. 88–132.

Suggested Reading

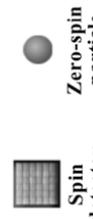
Davies and Brown, *The Ghost in the Atom*, especially Chapter 1.

Lindley, *Where Does the Weirdness Go?*, pp. 133–148.

Questions to Consider

1. Does the “uncertainty” of quantum physics, with its seeming measurer-measured interconnectedness, have any parallels in other areas of modern thought? (This is an epistemological question—what can we know and how can we know it? Is anything certain and on what basis can we assert it is?)
2. Review newspapers and news magazines (not specialized scientific publications) for articles on quantum physics, say for one month. How many articles did you find? How well did they explain things (based on what you know from this course)? Did they offer any “practical” application of the latest findings? Do you think that quantum physics is important in everyday life?

Einstein-Podolsky-Rosen Experiment

A  **Spin detector** **Zero-spin particle**

A zero-spin particle has some chance of decaying into two particles whose spins must add to the original spin value of zero. Here we see the zero-spin particle sitting near a spin detector.

B  **Spin detector**

The original particle has decayed, producing two particles traveling in opposite directions. At this point we don't know either particle's spin-and quantum physics says they have no definite spins until they're measured.

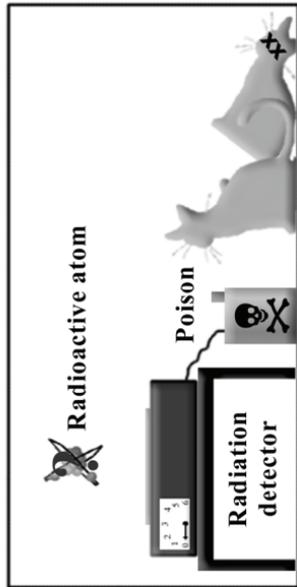
C  **Spin detector**

The left-hand particle has passed through the detector, which has determined that its spin is upward.

D  **Spin detector**

Because the spins must add to zero, we now know that the right-hand particle must have downward spin-even though we haven't measured it. And because the left-hand particle had no definite spin value before it passed through the detector, the right-hand particle's spin was somehow instantaneously established when the detector measured the left-hand particle's spin.

Schrödinger's Cat



Schrödinger's famous thought experiment shows how quantum ideas applied at the macroscopic level can lead to disturbing conclusions. The experiment consists of a radioactive atom with a 50 percent chance of decaying in one hour. A radiation detector signals when the decay occurs, and is connected so as to open the lid on a bottle of poison. This diabolical apparatus is sealed up in a box that also contains a live cat. Thus the fate of the cat is determined by a random, subatomic event.

If we seal up the box and wait an hour, what state will the cat be in? Classical physics says it will be either dead or alive, even if we haven't opened the box. But in the standard interpretation of quantum physics it makes no sense to talk about quantities that can't be measured. As long as the box is closed, we can't "measure" whether the cat is dead or alive. Therefore, according to the standard interpretation, the cat is in a "superposition" of dead and alive. After one hour there's a 50-50 chance that the atom will have decayed, so the cat is in an equal mix of dead or alive. Opening the box constitutes "measuring" the cat's state and thus leads to a definitive answer to the question "dead or alive?"

The Particle Zoo

Lecture 22

... [W]e're going to resume our descent into the heart of matter. We're going to resume a search for the ultimate constituents of everyday matter—bizarre, exotic matter—all the matter that makes up the universe.

By the early 20th century, physicists were aware of several atomic particles and, over the next decades, using “atom smashers,” they learned of many more. This created a complexity that by the end of the century scientists had largely “simplified.”

We move from macroscopic object to molecule (e.g., water) to nucleus and electrons of the atom (think of Rutherford's model). Electrons appear to be truly elementary, indivisible constituents of matter. The atomic nucleus is made up of *protons* and *neutrons*, collectively called *nucleons*.

Nucleons are made of still smaller *quarks*, believed to be truly elementary or fundamental. Quarks carry fractional electric charges ($\pm 2/3$ or $\pm 1/3$) of the electron charge. They are described as “up” and “down” quarks, depending on the charge. Quarks combine in threes to make protons, neutrons, and a host of other particles, collectively called *hadrons* (heavy particles), that were once thought to be elementary. Hadrons other than protons and neutrons are unstable, eventually decaying into other particles. Quarks also combine in twos to make another class of particles called *mesons*.

Gravity is the weakest of the forces. It is at once the most obvious to us and, in many ways, the least understood.

Today, physicists recognize just three fundamental forces that are responsible for all interactions in nature. Most believe that the three will someday be understood as aspects of a single, underlying force (more on this in Lecture 24). *Gravity* is the weakest of the forces. It is at once the most obvious to us and, in many ways, the least understood.

Gravity is universal; every bit of matter gives rise to gravity and every bit of matter responds to gravity. The general theory of relativity is our description of gravity; i.e., gravity is the geometrical structure of spacetime.

The *electroweak* force comprises the electromagnetic force (as described by Maxwell's equation) and the so-called *weak nuclear force*. The electromagnetic force is responsible for the structure of everyday matter from the scale of atoms on up. The weak nuclear force mediates certain nuclear processes, including nuclear reactions that make the Sun shine. The *color force*, also called the *strong force*, acts between quarks, binding them together to make hadrons and mesons. Unlike gravity and the electroweak force, the color force does not decrease in strength with increasing distance between the particles. For that reason, it appears impossible to separate quarks, and isolated quarks have never been observed. The residual color force between quarks in different nucleons provides the *nuclear force* that binds atomic nuclei together.

All matter is composed of two basic types of particles, which interact via the fundamental forces. One of these basic types is the quark. The other is the lepton, or "light" particle. Leptons include electrons and related particles and the elusive neutrinos.

There are three families of particles, each including two quarks, an electron-like particle, and a neutrino. Everyday matter is composed of particles from the first family. These include the up quark, the down quark, the electron, and the electron neutrino. The second family includes the charmed quark, the strange quark, the muon (as in the time-dilation experiments from Lecture 9), and the muon neutrino. The third family includes the top quark, the bottom quark, an electron-like particle termed the tau particle, and the tau neutrino. Discovery of the top quark in the mid-1990s completed verification of the three-family structure of the standard model.

Particles in the second and third families are more massive and, therefore, require more energy to create. All are unstable, which is why they aren't normally found. They can be created in particle accelerators and in high-energy astrophysical processes and were important in the early history of

the universe. Experiments show that there probably cannot be additional families of matter.

In addition to the matter particles are particles called *force carriers*. In the quantum description, a force between two particles involves an exchange of a third particle—the force carrier. The force carrier for the electromagnetic force is the familiar photon; for the weak force, the carrier is the *W* and *Z bosons*; for the color force, it's the *gluon*. For gravity, the force carrier would be the *graviton*—although this awaits a successful quantum theory of gravity (more on this in Lecture 24).

Finally, a massive particle called the *Higgs boson* should exist and, if it does, is responsible for the other particles' masses. Particle accelerators becoming operational around 2005 may be able to produce the Higgs particle. ■

Essential Reading

Kaku, *Hyperspace*, Chapter 5.

Kane, *The Particle Garden*.

Spielberg and Anderson, *Seven Ideas that Shook the Universe*, Chapter 8.

Suggested Reading

Lederman, *The God Particle*.

Pagels, *The Cosmic Code*, Chapters 3–11.

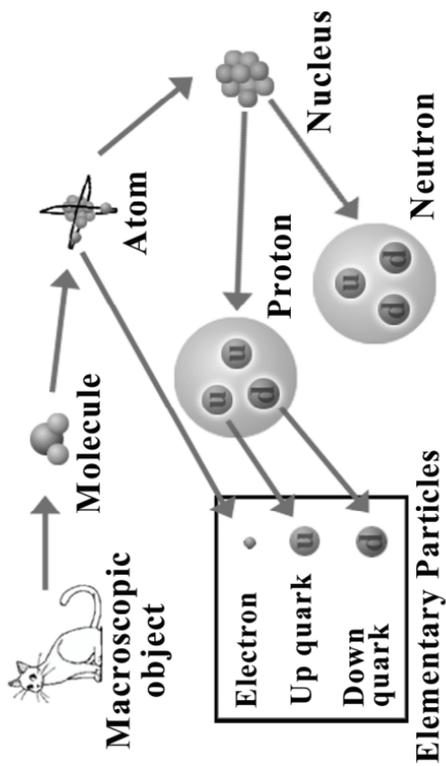
Riordan, *The Hunting of the Quark*.

Questions to Consider

1. If we can never isolate an individual quark, how can we possibly say that these particles exist? For that matter, we can't see electrons, protons, and neutrons either, and we have only the most rudimentary images of atoms. How do we know these particles exist?

2. How can atomic nuclei stick together? They contain only positively charged protons and neutral neutrons, so the electrical repulsion of the protons should tear them apart.

The Structure of Matter



Force in Quantum Physics (exchange of a "virtual particle")

Example: the electromagnetic force:



Force carrying particles:

- Electromagnetic force: photon
- Weak force: W, Z boson
- Color force: gluon
- (gravity): (graviton)

Cosmic Connections

Lecture 23

The bottom line is we know now that we live in a universe that is expanding and that appears to have had a definite beginning. There are three main lines of experimental evidence that lead us to that conclusion, and I want to describe those for you in some detail.

In the 1920s, Edwin Hubble (for whom the Hubble Space Telescope is named) discovered, using the Doppler shift, that distant galaxies are all moving away from us with speeds proportional to how far away they are. Hubble had discovered the *expansion of the universe*. It's important to keep in mind that this does not imply that we're at the center. Every observer sees the same thing. Each is like a raisin in a rising loaf of raisin bread; each raisin sees all others moving away with speeds proportional to their distance. An obvious implication of cosmic expansion is that the matter in the universe was once much more densely packed. Extrapolating back in time from the observed expansion suggests that the universe began in a *Big Bang* explosion some 15 billion years ago.

In the 1960s, Arno Penzias and Robert W. Wilson discovered the *cosmic microwave background radiation*. This was radiation left over from the time the universe first became transparent, about half a million years after the Big Bang. Cosmic background explorer (COBE) satellite studies of the microwave background in the 1990s showed it to be remarkably similar in every direction, but with tiny “ripples” that may be the seeds of the large-scale structure (galaxies and clusters of galaxies) that we see today.

The standard model of particles and forces allows us to explore conditions that would have held in the first instants after the Big Bang. The model predicts particle interactions that would lead to a distribution of matter similar to what is, in fact, observed. Thus, particle physics helps confirm the Big Bang concept.

The main theme of cosmic evolution is that, as the universe expands, it cools, allowing ever more complex structures to form. Here are some highlights of

the story of the universe during its expansion: At about 10 microseconds, nucleons formed from a “quark soup.” Within the first three minutes, helium nuclei formed. At about half a million years, electrons surrounded nuclei to make atoms, creating a transparent universe and producing the cosmic microwave background in the process. When the universe had reached 100 million to several billion years of age, galaxies formed. Later came the production of heavier elements, including carbon, oxygen, and others needed for life by nuclear fusion in stars. Supernova explosions spewed heavy elements into space. New stars and planets formed. Eventually life and intelligence evolved.

Change is essential to this story, and general relativity shows that the universe must be expanding or contracting (although the 1998 discovery that the expansion is accelerating rather than slowing muddies the simple picture). There are essentially two possibilities: either the universe will expand forever, or it will eventually contract in a “big crunch”—just as a ball thrown upward may escape Earth forever if its speed exceeds escape speed but will otherwise return.

Current theories suggest an *inflationary universe*, in which a period of very rapid expansion very early in the Big Bang (at 10^{-34} seconds!) smoothed out large-scale curvature to produce a universe whose overall geometry is flat—and, thus, barely able to expand forever. This inflationary scenario solves several outstanding problems with the Big Bang theory. However, it requires a higher density of matter than we’ve yet detected in the visible glow from stars and luminous gas or even in the gravitational influence of *dark matter* in galaxies. A sobering thought is that cosmologists now believe that most of the mass in the universe cannot even be in the form of ordinary matter but must consist of hitherto unknown forms of matter and/or energy. The universe we see and detect may be just a tiny fraction of what’s really there.

**We’re literally
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We're literally "children of the stars"; the elements that make up our bodies were forged in the cores of stars that have long since exploded. Physicist Freeman Dyson imagines that intelligence may persist to the infinite future, even as the universe evolves through an unimaginable richness of new forms and structures. ■

Essential Reading

Kaku, *Hyperspace*, Chapters 13–15.

Lightman, *Ancient Light*.

Weinberg, *The First Three Minutes*.

Suggested Reading

Barrow and Silk, *The Left Hand of Creation*.

Hawkins, *Hunting Down the Universe*.

Mather and Boslough, *The Very First Light*.

Padmanabhan, *After the First Three Minutes*.

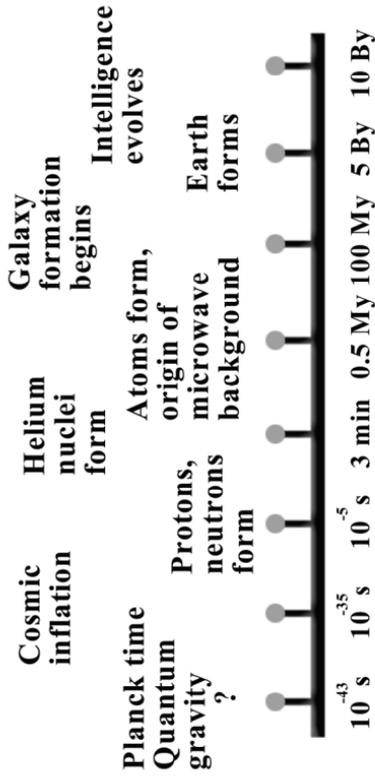
Questions to Consider

1. If we see all the distant galaxies receding from us, why can't we conclude that we're at the center of the universe?
2. Why couldn't atoms, or even nuclei, exist at the very earliest instants of the universe?
3. Freeman Dyson's vision of intelligence in a forever-expanding universe imbues intelligent life with a kind of immortality. Discuss this concept and examine how cosmic expansion and Dyson's vision affect your feelings about your own mortality.

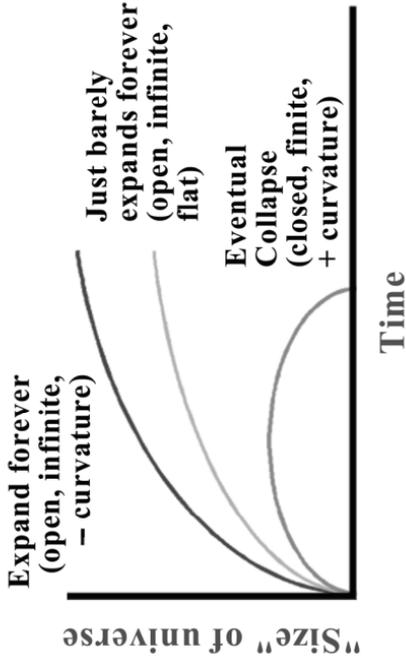
For more treatment of the topics covered in this lecture, we recommend The Teaching Company course *Understanding the Universe: An Introduction to Astronomy, 2nd Edition* by Professor Alex Filippenko of the University of California at Berkeley. Professor Filippenko led the team that demonstrated the accelerating expansion of the universe in 1998.

A Cosmic Timeline

(approximate and not to scale)



Cosmic Futures



Toward a Theory of Everything

Lecture 24

We know how general relativity can lead to an understanding of the overall structure of the universe, raising the question: Is the universe closed or open? Will it expand forever, or will it eventually close? Do we, then, know everything there is to know? Can we explain everything that needs to be explained about our universe? The answer is, clearly, no, and for several reasons.

General relativity describes the properties of the universe at the large scale: the overall curvature of the universe, the curved spacetime around gravitating masses, the behavior of matter near a black hole. Quantum physics, in contrast, describes the universe at small scales. In nearly all of physics, one or the other of these two theories suffices.

There are, however, situations in which intense gravity—spacetime curvature—exists on very small scales and to describe these, we need to merge general relativity with quantum physics to make a theory of *quantum gravity*. Quantum gravity becomes important on scales of around the so-called *Planck length*, about 10^{-33} centimeters. (That's 1/1,000,000,000,000,000,000,000,000,000,000 of a centimeter.) At this scale, fluctuations in the structure of spacetime required by the uncertainty principle become huge. (Recall that confining matter to a small space means a large uncertainty in velocity—and that implies a large velocity and a large energy.) Quantum gravity must be important at the very centers of black holes, where general relativity predicts that matter is crushed to infinite density in a space of zero size. Quantum gravity must have been important in the history of the universe before the *Planck time*, about 10^{-43} seconds after the Big Bang.

A brief history of physics shows a common theme: the merging of distinct fields and phenomena under ever broader, more encompassing theories. Newton's theories of motion and gravity subsumed celestial and terrestrial motion under the same set of laws. The work of Maxwell and others in the 19th century joined electricity and magnetism under the theory of electromagnetism; soon optics joined them, when Maxwell realized that light

was an electromagnetic wave. Special relativity and quantum physics were successfully merged in 1948 with the theory of *quantum electrodynamics*.

Theoretical work in the 1970s, followed by experiments in the 1980s, confirmed the *electroweak theory*'s unification of electromagnetism with the weak nuclear force. Unification of the color force (described by the theory of *quantum chromodynamics*) and the electroweak force appears to be in sight; the resulting *grand unified force* would explain all physical phenomena except those involving gravity. The ultimate *theory of everything* will require a merger of general relativity with quantum physics to make a theory of *quantum gravity*.

String theory may lead the way to this *theory of everything*. String theory arose around 1970, enjoyed a brief heyday in the mid-1980s, then faded because of seemingly insurmountable problems. In 1995, string theory had a dramatic comeback and today, string theorists are hard at work exploring the theory and its implications. Some—but not all—physicists are optimistic that this work may lead to the theory of everything. However, string theory still presents as-yet-unsolved mathematical problems, and no version of string theory has yet produced a full, quantitatively correct explanation for all the forces and particles of nature.

In string theory, the fundamental entities are not particles but tiny, string-like loops, whose size is roughly the Planck length at which the incompatibility between general relativity and quantum physics arises. Different vibrations of the strings correspond to the different “elementary” particles, just as different vibrations of a violin string make different notes. In this sense, all particles are aspects of a single underlying entity—the string. String theory not only shows how the individual particles arise, but it also predicts their masses—something that the standard model of particles and fields cannot do. Because the size of the strings is roughly the Planck length and because strings are the most fundamental entities there are, it makes no sense to talk about what happens on scales smaller than the Planck length. Thus, string theory sidesteps the conflict between quantum theory and general relativity by simply avoiding the regime in which the conflict occurs. Because a string is an extended object, the interaction between two particles occurs not at a point in space and an instant in time, but is spread out over time and space.

In particular, different observers see different parts of the strings interacting at different times, so there can be no unambiguous point and time where the interaction occurs. In the mathematics of string theory, this has the effect of eliminating the infinite spacetime curvature that would occur with true point particles.

An essential requirement of string theory is that the strings exist not in the four dimensions of ordinary spacetime (three of space, one of time), but in a spacetime of as many as 11 dimensions. Unlike the dimensions we're used to, the "extra" dimensions don't extend forever, but are curled up into tiny, closed structures on scales so small even quarks can't move in the extra dimensions. But the strings are small enough to vibrate in the extra dimensions. This effect gives string theory some of its richness and its ability to explain the diversity of particles we observe in the world.

An analogy can help us to understand how there can be extra dimensions we don't notice (adapted from Green, *The Elegant Universe*): Imagine a bug walking along a tightly stretched, cylindrical rope. From a distance, it looks as if the bug lives in a one-dimensional world; it can move back and forth *along* the rope, but has no other freedom of motion. But move in close and you see that the bug can move in a second dimension. This is the dimension *around* the rope. This dimension doesn't extend a great distance like the length of the rope, but wraps around in a limited space. If the bug is much bigger than the rope diameter, it won't even notice the extra dimension. The extra dimensions of string theory are like this, except that they involve shapes much more complicated than the cylinder of the rope, and there are seven of them.

An essential requirement of string theory is that the strings exist not in the four dimensions of ordinary spacetime (three of space, one of time), but in a spacetime of as many as 11 dimensions.

If we achieve a theory of everything, will that be the end of physics? No! There are still plenty of everyday phenomena we haven't yet explained—even though we're sure their explanations follow from the known laws of physics. Remember the dark matter: We still don't have any idea what most

of the universe is made of! Remember Dyson: We may have an infinity of time to explore the richness of our evolving universe. Stay tuned! ■

Suggested Reading

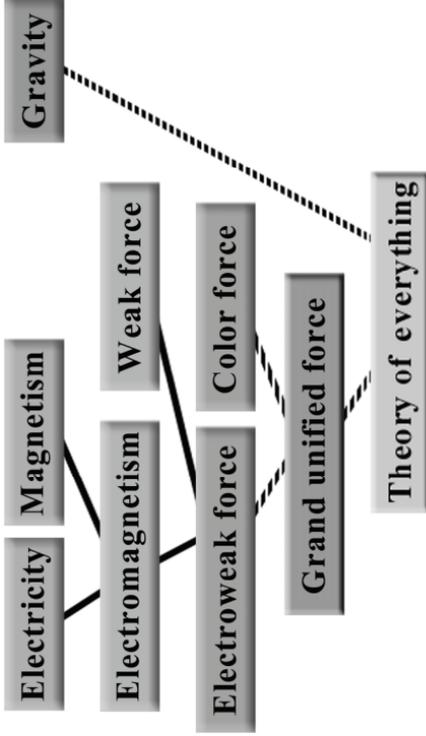
Green, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*.

Kaku, *Hyperspace*, Chapters 5–9.

Questions to Consider

1. This isn't really a question, but rather a task. Look for articles in the newspaper or in magazines that you read that deal with the latest developments in science and find those that cover relativity and quantum physics. See in what way they expand on or change what you have learned in this course.
2. Do you think it is possible to have a "theory of everything?" Defend your answer.

Unification of the Fundamental Forces



"Curled Up" Dimensions



One of the difficulties with string theories is that they require many more dimensions than the four dimensions of ordinary spacetime. Some versions of string theory require as many as 11 dimensions. So where are the extra seven dimensions?

According to string theory, these dimensions are "curled up" or "compactified" on such very small length scales that they are not noticed in our everyday lives or even in subatomic physics experiments. This diagram shows an analogy in fewer dimensions. At the top we see an ant on a rope. Viewed from a distance, it looks like the ant can move in only one dimension, namely back and forth along the rope. But if we get very close we can see that the ant can move in two mutually perpendicular directions, either along the rope or around it. The around-the-rope dimension is a "curled-up" dimension, evident only when the system is examined on very small length scales. This around-the-rope dimension is analogous to the extra dimensions in string theory.



Timeline

- 1543..... Copernicus publishes *De Revolutionibus Orbium Coelestium*, challenging the then-held view that Earth was at the center of the universe.
- 1686..... Newton completes the *Principia Mathematica*, which includes his laws of motion and theory of gravity.
- 1801..... Young's double-slit experiment shows that light is a wave.
- 1860..... Maxwell completes the synthesis of the four equations of electromagnetism and shows that they imply electromagnetic waves that propagate at the speed of light.
- 1887..... The Michelson-Morley experiment fails to detect Earth's motion through the ether.
- 1897..... J. J. Thomson discovers the electron.
- 1900..... Planck resolves the ultraviolet catastrophe by postulating quantization of the energy associated with hot, glowing objects.
- 1905..... Einstein explains the photoelectric effect by proposing that light energy is quantized.
- 1905..... Einstein publishes the special theory of relativity.

1911.....	Rutherford discovers the atomic nucleus and proposes his “solar system” model for the atom.
1913.....	Bohr publishes his quantum theory of the atom.
1916.....	Einstein publishes the general theory of relativity.
1919.....	Observations by Eddington and colleagues at a total solar eclipse confirm general relativity’s predictions of the bending of light by the Sun’s gravity.
1923.....	DeBroglie sets forth his matter-wave hypothesis. Compton effect experiment convinces most skeptics of the reality of quanta.
1927.....	Heisenberg states the uncertainty principle. Davisson and Germer show that electrons undergo interference, thus experimentally verifying DeBroglie’s matter-wave hypothesis.
1929.....	Hubble discovers the expansion of the universe.
1932.....	Carl Anderson discovers the positron, verifying Dirac’s hypothesis that antimatter should exist.
1939.....	Lise Meitner identifies the process of nuclear fission.
1948.....	Feynman, Tomonaga, and Schwinger produce the theory of quantum electrodynamics, successfully uniting special relativity with quantum mechanics.

1964.....	Quarks proposed as fundamental constituents of matter.
1965.....	Penzias and Wilson discover cosmic microwave background radiation.
1983.....	Experimental verification of electroweak unification.
1994.....	Existence of the top quark is experimentally verified.
1995.....	Second string theory revolution increases interest in string theory as a possible “theory of everything.”
1998.....	Neutrinos found to have nonzero mass. Cosmic expansion of the universe found to be accelerating.

Glossary

aberration of starlight: A phenomenon whereby a telescope must be pointed in slightly different directions at different times of year, because of Earth's orbital motion. The fact of aberration shows that Earth cannot drag with it the ether in its immediate vicinity and, thus, helps dispel the notion that ether exists.

absolute motion: Motion that exists, undeniably, without reference to anything else. The relativity principle denies the possibility of absolute motion.

Big Bang: The explosive event that began the expansion of the universe.

black hole: An object so small yet so massive that escape speed exceeds the speed of light. General relativity predicts the possibility of black holes, and modern astrophysics has essentially confirmed their existence.

color force: The very strong force that acts between quarks, binding them together to form hadrons and mesons.

Compton effect: An interaction between a photon and an electron, in which the photon scatters off the electron, as in a collision between billiard balls, and comes off with less energy. The effect provides a convincing demonstration of the quantization of light energy.

Copenhagen interpretation of quantum physics: The standard view of the meaning of quantum physics, which states that it makes no sense to talk about quantities, such as the precise velocity and position of a particle, that cannot even in principle be measured simultaneously.

cosmic microwave background: "Fossil" radiation from the time 500,000 years after the Big Bang, when atoms formed and the universe became transparent.

dark matter: Matter in the cosmos that is undetectable because it doesn't glow. Dark matter, some of it in the form of as-yet-undiscovered exotic particles, is thought to comprise most of the universe.

electromagnetic wave: A structure consisting of electric and magnetic fields in which each kind of field generates the other to keep the structure propagating through empty space at the speed of light, c . Electromagnetic waves include radio and TV signals, infrared radiation, visible light, ultraviolet light, x rays, and gamma rays.

electroweak force: One of the three fundamental forces now identified, the electroweak force subsumes electromagnetism and the weak nuclear force.

elsewhere: A region of spacetime that is neither past nor future. The elsewhere of a given event consists of those other events that cannot influence or be influenced by the given event—namely, those events that are far enough away in space that not even light can travel between them and the given event.

escape speed: The speed needed to escape to infinitely great distance from a gravitating object. For Earth, escape speed from the surface is about 7 miles per second; for a black hole, escape speed exceeds the speed of light.

ether: A hypothetical substance, proposed by 19th century physicists and thought to be the medium in which electromagnetic waves were disturbances.

event horizon: A spherical surface surrounding a black hole and marking the “point of no return” from which nothing can escape.

field: A way of describing interacting objects that avoids action at a distance. In the field view, one object creates a field that pervades space; a second object responds to the field in its immediate vicinity. Examples include the electric field, the magnetic field, and the gravitational field.

frame of reference: A conceptual framework from which one can make observations. Specifying a frame of reference means specifying one's state of motion and the orientation of coordinate axes used to measure positions.

general theory of relativity: Einstein's generalization of special relativity that makes all observers, whatever their states of motion, essentially equivalent. Because of the equivalence principle, general relativity is necessarily a theory about gravity.

geodesic: The shortest path in a curved geometry, like a great circle on Earth's surface. Objects that move freely follow geodesics in the curved spacetime of general relativity.

gravitational lensing: An effect caused by the general relativistic bending of light, whereby light from a distant astrophysical object is bent by an intervening massive object to produce multiple and/or distorted images.

gravitational time dilation: The slowing of time in regions of intense gravity (large spacetime curvature).

gravitational waves: Literally, "ripples" in the fabric of spacetime. They propagate at the speed of light and result in transient distortions in space and time.

gravity: According to Newton, an attractive force that acts between all matter in the universe. According to Einstein, a geometrical property of spacetime (spacetime curvature) that results in the straightest paths not being Euclidean straight lines.

hadron: A "heavy" particle, made up of three quarks. Protons and neutrons are the most well known hadrons.

Heisenberg uncertainty principle: The statement that one cannot simultaneously measure both the position and velocity (actually, momentum) of a particle with arbitrary precision.

interference: A wave phenomenon, whereby two waves at the same place simply add together to make a composite wave. When both waves reinforce, the interference is said to be constructive and results in a stronger wave. When the waves tend to cancel each other, the interference is destructive. Interference is useful in precision optical measurements, including the Michelson-Morley experiment.

length contraction: The phenomenon whereby an object or distance is longest in a reference frame in which the object or the endpoints of the distance are at rest. Also called the *Lorentz contraction* and *Lorentz-Fitzgerald contraction*.

lepton: Collective name for the light particles electron, muon, tau, and their associated neutrinos.

mass-energy equivalence: The statement, embodied in Einstein's equation $E=mc^2$, that matter and energy are interchangeable.

Maxwell's equations: The four equations that govern all electromagnetic phenomena described by classical physics. It was Maxwell in the 1860s who completed the full set of equations and went on to show how they predict the existence of electromagnetic waves. Maxwell's equations are fully consistent with special relativity.

mechanics: The branch of physics dealing with the study of motion.

meson: A particle made up of two quarks (actually, a quark and an antiquark).

Michelson-Morley experiment: An 1880s experiment designed to detect Earth's motion through the ether. The experiment failed to detect such motion, paving the way for the abandonment of the ether concept and the advent of relativity.

neutrino: An elusive particle with very small mass that arises in weak nuclear reactions.

neutron star: An astrophysical object that arises at the end of the lifetime of certain massive stars. A typical neutron star has the mass of several Suns crammed into a ball with a diameter about that of a city.

photoelectric effect: The ejection of electrons from a metal by the influence of light incident on the metal.

photon: The quantum of electromagnetic radiation. For radiation of frequency f , the quantum of energy is $E = hf$.

Planck's constant: A fundamental constant of nature, designated h , that sets the basic scale of quantization. If h were zero, classical physics would be correct; h being nonzero is what necessitates quantum physics.

Principle of Complementarity: Bohr's statement that wave and particle aspects of nature are complementary and can never both be true simultaneously.

Principle of Equivalence: The statement that the effects of gravity and acceleration are indistinguishable in a sufficiently small reference frame. The principle of equivalence is at the heart of general relativity's identification of gravity with the geometry of spacetime.

Principle of Galilean Relativity: The statement that the laws of motion are the same in all uniformly moving frames of reference; equivalently, such statements as "I am moving" or "I am at rest" are meaningless unless "moving" and "rest" are relative to some other object or reference frame.

quanta: Discrete, indivisible "chunks" of a physical quantity, such as energy.

quark: A fundamental particle, building block of protons and neutrons, as well as all other hadrons and mesons. There are six different quarks, two in each of the three families of matter.

relativistic invariant: A quantity that has a value that is the same in all frames of reference. The spacetime interval is one example of a relativistic invariant.

relativity principle: A statement that only relative motion is significant. The principle of Galilean relativity is a special case, applicable only to the laws of motion. Einstein's principle of special relativity covers all of physics but is limited to the case of uniform motion.

spacetime: The four-dimensional continuum in which the events of the universe take place. According to relativity, spacetime breaks down into space and time in different ways for different observers.

spacetime curvature: The geometrical property of spacetime that causes its geometry to differ from ordinary Euclidean geometry. The curvature is caused by the presence of massive objects, and other objects naturally follow the straightest possible paths in curved spacetime. This is the essence of general relativity's description of gravity.

spacetime interval: A four-dimensional "distance" in spacetime. Unlike intervals of time or distance, which are different for observers in relative motion, the spacetime interval between two events has the same value for all observers.

special theory of relativity: Einstein's statement that the laws of physics are the same for all observers in uniform motion.

string theory: A description of physical reality in which the fundamental entities are not particles but tiny string-like loops. Different oscillations of the loops correspond to what we now consider different "elementary" particles. String theory is a leading candidate for a "theory of everything."

time dilation: In special relativity, the phenomenon whereby the time measured by a uniformly moving clock present at two events is shorter than that measured by separate clocks located at the two events. In general relativity, the phenomenon of time running slower in a region of stronger gravity (greater spacetime curvature).

ultraviolet catastrophe: The absurd prediction of classical physics that a hot, glowing object should emit an infinite amount of energy in the short-wavelength region of the electromagnetic spectrum.

universal gravitation: The concept, originated by Newton, that every piece of matter in the universe attracts every other piece.

wave packet: A construction made from waves of different frequencies that results in a localized wave disturbance.

white dwarf: A collapsed star with approximately the mass of the Sun crammed into the size of the Earth.

wormhole: A hypothetical “tunnel” linking otherwise distant regions of spacetime.

Bibliography

To the Student/Reader: It is difficult to find readings that exactly parallel the structure of the lectures. The readings I've chosen are designed to extend and complement the lectures, rather than to repeat the lecture material. Most of the materials chosen, even those in the "Suggested Reading" category, are aimed at lay audiences. Motivated readers will find more in-depth and mathematically oriented coverage of these topics in science textbooks, especially at the college level. The books listed here include a mix of older and more contemporary works. Many good books on the development of modern physics are now quite dated and out of print, but they still provide excellent introductions to the subject. Books listed under "Essential Reading" are in print as of 1999; some of the others are out of print but should be available in most public libraries. New books on the more contemporary subjects covered in these lectures are published each year.

Barrow, John D., and Silk, Joseph, *The Left Hand of Creation: The Origin and Evolution of the Expanding Universe* (Oxford University Press, 1993). This overview of cosmology, originally published in 1983 and updated 10 years later, is particularly good on the relation between particle physics and cosmology.

Brennan, Richard, *Heisenberg Probably Slept Here: The Lives, Times, and Ideas of the Great Physicists of the 20th Century* (John Wiley & Sons, 1997). Part biography, part science, this book details the lives and contributions of Newton (even though he's not from the 20th century), Einstein, Planck, Rutherford, Bohr, Heisenberg, Feynman, and Gell-Mann. Notably absent are the great female physicists of the century, most of whom made their contributions in nuclear physics: Nobel laureates Marie Curie (two Nobel Prizes) and her daughter Irène; Maria Goeppert Mayer, Nobel laureate for her contributions to nuclear theory; and Lise Meitner, who first identified the process of nuclear fission.

Casper, Barry, and Noer, Richard, *Revolutions in Physics* (New York, W. W. Norton, 1972). Used in college science courses for nonscience students, this

well-written book describes a number of important revolutions in ideas about the physical world, including but not limited to those of modern physics.

Calaprice, Alice, ed., *The Quotable Einstein* (Princeton University Press, 1996). Need a quote by Einstein on your favorite subject? You'll find it all here—from religion to science to marriage to music to vegetarianism to abortion to capitalism to sailing, and much more!

Daintith, John, Mitchell, Sarah, Tootill, Elizabeth, and Gjertsen, Derek, *Biographical Encyclopedia of Scientists* (Institute of Physics Publishing, 1994). A handy source of brief biographical sketches of major scientists, both historical and contemporary.

Davies, Paul, *About Time: Einstein's Unfinished Revolution* (New York: Simon and Schuster, 1995). Davies, winner of the Templeton Prize for Religion, is a prolific popularizer of science and an active researcher in gravitational physics. This book takes the reader on an exploration of the nature of time, well beyond what's covered in this lecture series.

Davies, P. C. W., and Brown, J. R., eds., *The Ghost in the Atom* (Cambridge University Press, 1986). This book introduces the strange concepts of quantum physics and provides transcripts of question-and-answer sessions with some of the leading physicists concerned with interpretations of quantum physics.

Einstein, Albert, and Infeld, Leopold, *The Evolution of Physics*, (Simon & Schuster, 1967 and earlier editions). This old classic presents the conceptual background behind the development of relativity. Although not as lively as some contemporary works, it's good to hear about relativity in Einstein's own words (and those of his colleague, Infeld).

French, A. P., ed., *Einstein: A Centenary Volume* (Harvard University Press, 1979). This work was produced by the International Commission on Physics Education in celebration of the hundredth anniversary of Einstein's birth. The interested reader will find here a wealth of historical, biographical, and scientific perspective on Einstein's life and work, including translations of some original Einstein writings.

Fritzsche, Harald, *An Equation that Changed the World* (University of Chicago Press, 1994). There's more emphasis here than I would like on $E=mc^2$, but this book still provides a good introduction to relativity.

Greene, Brian, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory* (W.W. Norton, 1999). This lively and very contemporary book is written at just the right level for a layperson interested in really understanding what string theory is about. Author Greene, himself a string theory researcher, concentrates on the revolution in string theory of the mid-1990s and communicates his enthusiasm for a theory he believes really has the makings of the "theory of everything."

Gribbin, John, *In Search of Schrödinger's Cat: Quantum Physics and Reality* (Bantam Books, 1984). A good book for nonscientists on the basics of quantum physics, which then goes on to give clear descriptions of such "quantum weirdness" as Schrödinger's cat and EPR experiments. As the paperback edition's cover says: "A fascinating and delightful introduction to the strange world of the quantum..."

Hafele, J. C., and Keating, Richard, "Around-the-World Atomic Clocks: Predicted Relativistic Time Gains" and "Around-the-World Atomic Clocks: Observed Relativistic Time Gains," *Science*, vol. 177, pp. 166–170 (July 1972). These back-to-back scientific papers describe in detail the background and experiments on relativistic time dilation using atomic clocks. Both special and general relativistic effects are covered. There's a good bit of math. *Science* is a general publication for scientists, so this is not just for relativity experts.

Han, M. Y., *The Probable Universe: An Owner's Guide to Quantum Physics* (Summit, PA: TAB Books/McGraw-Hill, 1993). This short book provides a brief introduction to the ideas of quantum physics, then goes on to its many contemporary practical applications, such as tunneling microscopy, microelectronic devices, and more. Color plates of tunneling microscope photos show just how far technology can go in manipulating individual atoms.

Hawkins, Michael, *Hunting Down the Universe: The Missing Mass, Primordial Black Holes and Other Dark Matters* (Little, Brown, 1997). This is a cosmology book with an emphasis on contemporary problems and observational evidence in cosmology.

Heisenberg, Werner, *Physics and Philosophy: The Revolution in Modern Science* (New York: Harper, 1962; also republished by Prometheus Books, Amherst, NY, 1999). In his later years Heisenberg turned increasingly to philosophical issues. This book sets forth his views, especially on the interpretation of quantum physics.

Hey, Tony, and Walters, Patrick, *Einstein's Mirror* (Cambridge University Press, 1997). Written in a breezy, popular style and prolifically illustrated, this book presents the ideas of relativity intermixed with lots of modern technology and astronomy. Not the most coherent presentation of relativity but fun to read.

———, *The Quantum Universe* (Cambridge University Press, 1987). An exposition of quantum physics, stylistically very similar to the authors' relativity book described above.

Kaku, Michio, *Hyperspace* (New York: Anchor Books, 1994). Kaku, a prolific science writer, provides a trendy look at modern physics, emphasizing string theory and the search for a "theory of everything."

Kane, Gordon, *The Particle Garden* (Addison Wesley, 1995). In this book, Kane, a particle physicist and popular lecturer, gives a clear, nonmathematical explication of the standard model of particles and forces.

Lasota, Jean-Pierre, "Unmasking Black Holes," *Scientific American*, vol. 280, no. 5, p. 40 (May 1999). In this article, an astrophysicist presents contemporary evidence for the reality of black holes.

Lederman, Leon (with Dick Teresi), *The God Particle: If the Universe Is the Answer, What Is the Question?* (Boston: Houghton Mifflin, 1993). A Nobel laureate and former director of the Fermi National Accelerator, Lederman

teams with Teresi, science writer and former editor of *Omni* magazine, in a lively look at the history and science of modern particle physics.

Lightman, Alan, *Ancient Light: Our Changing View of the Universe* (Harvard University Press, 1991). Lightman—scientist, science writer, and novelist—devotes a chapter to each of the main themes in modern cosmology. The book includes biographical sketches of leading cosmologists.

—————, *Great Ideas in Physics* (New York: McGraw-Hill, 1992). Lightman has chosen his favorite “big ideas” in physics. The sections on relativity provide good supplements to this course.

Lindley, David, *Where Does the Weirdness Go? Why Quantum Mechanics Is Strange but not as Strange as You Think* (Basic Books/HarperCollins, 1996). Lindley, formerly an astrophysicist at Cambridge and the Fermi National Accelerator Laboratory, later became an editor at the British science journal *Nature* and at *Science News*. *Where Does the Weirdness Go?* is an excellent introduction to quantum physics, with emphasis on such quandaries as Schrödinger’s cat, EPR experiments, and the general philosophical interpretation of quantum physics.

Mather, John C., and Boslough, John, *The Very First Light: The True Inside Story of the Scientific Journey Back to the Dawn of the Universe* (Basic Books, 1996). Mather, Project Scientist at NASA for the Cosmic Background Explorer (COBE) satellite, teams with science writer Boslough to explore the science, politics, and personalities behind our most detailed knowledge of the cosmic microwave background radiation.

Mermin, N. David, *It’s About Time: Understanding Einstein’s Relativity* (Princeton University Press, 2005). A well-written book suitable for those who want a more mathematical approach that doesn’t go beyond high-school algebra. Simple geometric diagrams reinforce the concepts and the math.

Mook, Delo, and Vargish, Thomas, *Inside Relativity* (Princeton University Press, 1987). A physicist and artist teamed up to ensure that this introduction to relativity would be truly comprehensible to nonscientists. And it is. It’s not flashy, but it provides a good, solid introduction to the subject.

Moore, Thomas, *A Traveler's Guide to Spacetime* (New York: McGraw-Hill, 1995). Written as a textbook for a month-long relativity segment in sophomore-level college physics courses, this book is much more mathematical than others in this bibliography, but it provides a lively, clear, and very contemporary look at its subject. Readers wanting more math would do well to read Moore.

Padmanabhan, T., *After the First Three Minutes: The Story of Our Universe* (Cambridge University Press, 1998). An astrophysicist outlines the history of the universe. Includes good background material on star formation and other relevant astrophysical processes. The title is a takeoff on Weinberg's *The First Three Minutes*, listed below.

Pagels, Heinz, *The Cosmic Code: Quantum Physics as the Language of Nature* (New York: Simon and Schuster, 1982). This solid introduction to quantum physics for the nonscientist is, unfortunately, out of print.

Riordan, Michael, *The Hunting of the Quark* (Simon & Schuster, 1987). This book gives a history of particle physics, especially the quark concept, that emphasizes the personalities and interactions of the scientists and scientific teams involved in particle theories and experiments.

Sime, Ruth, *Lise Meitner: A Life in Physics* (University of California Press, 1996). A scholarly but eminently readable account of the life of Lise Meitner, the nuclear physicist who identified the process of nuclear fission.

Spielberg, Nathan, and Anderson, Byron D., *Seven Ideas that Shook the Universe* (Wiley, 1985). Among the "universe shaking" ideas covered in this book are some from quantum physics; see Chapters 7 and 8.

Taylor, Edwin, and Wheeler, John Archibald, *Spacetime Physics*, 2nd edition (New York: W. H. Freeman, 1992). John Archibald Wheeler of Princeton is one of the leading American physicists of the century. Wheeler and MIT physicist Edwin Taylor have produced a book aimed at college physics students but emphasizing the conceptual essence of relativity. Written in a lively but slightly quirky style, this book presents special relativity in a way that prepares the reader for the curved spacetime of the general theory. The

authors do not avoid math, but the conceptual aspects of relativity are always in the forefront.

Thorne, Kip, *Black Holes and Time Warps: Einstein's Outrageous Legacy* (New York: W. W. Norton, 1994). Thorne, a leading researcher on black holes and general relativity, has written a lively and up-to-date book for nonscientists. A good introduction to relativity is followed by convincing arguments for why black holes must exist.

Weinberg, Steven, *The First Three Minutes* (Basic Books, 1988). A noted theorist and winner of the 1979 Nobel Prize for physics details the first few minutes of creation, when a lot of important events happened that set the stage for all that followed.

Will, Clifford, *Was Einstein Right? Putting General Relativity to the Test* (New York: Basic Books, 1986). This book explores experimental tests of general relativity, both the “classic” tests, such as the bending of starlight and early gravitational time dilation experiments, to the even more convincing results from modern astrophysics. Its 1986 publication date makes it a bit dated in this rapidly advancing field, but the essential evidence for general relativity is all there.

Wheeler, John Archibald, *A Journey into Gravity and Spacetime* (New York: Scientific American Library, 1990). Wheeler, described under Taylor and Wheeler, above, has written this “coffee table” book with plenty of color pictures and few equations. As in *Spacetime Physics*, the emphasis is on the essential conceptual basis of general relativity.

Wolf, Fred Alan, *Taking the Quantum Leap* (New York: Harper & Row, 1989). Wolf, a former physics professor from San Diego State University, has written yet another good introduction to quantum physics for the nonscientist. Wolf’s book is particularly strong on the role of the observer in quantum measurements. Simple illustrations and catchy section titles help make this book an inviting introduction to the subject.

Wolfson, Richard. *Simply Einstein: Relativity Demystified* (W.W. Norton, 2003). Your Teaching Company professor elaborates on relativity, with explanations and diagrams that augment the presentation in this course.