Great Ideas of Classical Physics
Part I
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Steven Pollock is associate professor of physics at the University of Colorado, Boulder. He did his undergraduate work at MIT, receiving a B.Sc. in physics in 1982. He holds a master's and a Ph.D. in physics from Stanford University, where he completed a thesis on "Electroweak Interactions in the Nuclear Domain" in 1987. He did postdoctoral research at NIKHEF (the National Institute for Nuclear and High Energy Physics) in Amsterdam from 1988–1990 and at the Institute for Nuclear Theory in Seattle from 1990–1992. He spent a year as senior researcher at NIKHEF in 1993 before moving to Boulder.

From 1993–2000, Professor Pollock's research work focused on the intersections of nuclear and particle physics, with special focus on parity violation, neutrino physics, and virtual strangeness content of ordinary matter. Around the time he received tenure at CU Boulder, Professor Pollock began shifting his attention to the newly developing discipline-based research field of physics education research. This field now represents his full-time physics research activities.

Professor Pollock was a teaching assistant and tutor for undergraduates throughout his years as both an undergraduate and graduate student. As a college professor, he has taught a wide variety of university courses at all levels, from introductory physics to advanced nuclear and particle physics, including quantum physics (both introductory and senior level) and mathematical physics, with intriguing recent forays into the physics of energy and the environment and the physics of sound and music.

Professor Pollock is the author of *Thinkwell's Physics I*, a CD-based introductory physics "next-generation" multimedia textbook. He became a Pew/Carnegie National Teaching Scholar in 2001 and is currently pursuing classroom research into replication and sustainability of reformed teaching techniques in (very) large lecture introductory courses. Professor Pollock received an Alfred P. Sloan Research Fellowship in 1994, the Boulder Faculty Assembly (CU campus-wide) Teaching Excellence Award in 1998, and the Marinus G. Smith Recognition Award in 2006. He has presented both nuclear physics research and his scholarship on teaching at numerous conferences, seminars, and colloquia. He is a member of the American Physical Society, the Forum on Education, and the American Association of Physics Teachers.

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Part I

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Scope:

Physics is the science that tries to understand the deep principles underlying the world we live in. It's about understanding and describing nature. It's about *things*, as opposed to biological or even chemical *systems*. *How* do things move? *Why* do they move? How do they *work*? Physicists search for deep patterns, for the fundamental simplicity and unity of measurable phenomena. In this course, we will follow a theme-based, quasi-historical path, highlighting the central concepts, ideas, and discoveries of classical physics. *Classical* here refers to scientific work done up to the start of the 20th century, that is, essentially all physics before the quantum theory and relativity. It is the physics of everyday life, the physics of a deterministic "clockwork" universe, with enormous explanatory and predictive power! We will spend a little time getting to know the characters who played key roles, including Galileo, Newton, Faraday, Maxwell, and others, but the emphasis of the course is on sense-making: What have physicists learned about the world? What are the key underlying laws of nature? What are the primary organizing principles? How can we use these ideas and connect them to our personal experiences?

Physics is a broad field of study and can be approached from many angles. We begin with a venerable branch of physics known as *mechanics*, the study of forces, energy, and motion. The word *mechanics* might make one think of car engines, and in some ways, that's a good metaphor. Engines are complicated, but they are built out of simple and comprehensible parts, each of which serves a simple purpose. When put together, they create a familiar, useful, and understandable (by mechanics!) whole. But *mechanics* in physics is not about cars; it's the study of how just about anything moves and what makes objects behave as they do when acted on by forces. It's a study that will help us understand a vast and disparate array of phenomena, from Olympic high divers, to the display of sparks in a firework on the 4th of July, to the path of the Moon in the night sky, or the ceaseless bounce and jitter of atoms in a gas. We will focus on the central concepts: What do we know, and how do we know it? We'll ask where the ideas came from and how we might test them. And, of course, we'll ask what we can do with this knowledge. Classical mechanics is primarily the physics of Isaac Newton and a host of other brilliant characters who laid the groundwork for understanding the world that is still relevant 400 years after its beginnings. Our goal is to walk away with a sense of the order and coherence, the basic structure and principles of this foundation of physics.

Mechanics sits underneath the rest of physics a bit like the foundation of a great cathedral. The second half of the course will add the edifice, structure, and turrets. We will need to understand the ideas behind *electricity* and *magnetism*, forces that dominate our technological world and lead to understanding of the structure of all matter and light. This investigation leads naturally to *optics*, which was unified with electricity and magnetism in a brilliant stroke in the mid-1800s. In this context, we will briefly consider *waves* and the myriad phenomena that become understandable, and intimately related to one another, once we grasp the basic ideas and consequences of vibrations. We will need to learn separately about *heat* and *thermodynamics*, a branch of classical physics that deals with everything from understanding car engines and power supplies to making a perfect cake. This course of study takes us right up to the start of the 20th century.

One final comment: Mathematics plays a special role in science, one very dear to physicists, but we will not (and need not) focus on math in this course. Although skipping the equations limits, to some extent, the depth to which we can learn physics, the concepts themselves are, by and large, sensible, intuitive, and comprehensible through metaphor, life experience, ordinary logic, and common sense. From time to time, however, we may follow brief mathematical detours to appreciate the power and beauty of more formal or symbolic reasoning!

Notes on Course Materials: Suggested readings and computer simulations are listed with each lecture, using the abbreviations noted below.

Essential Computer Simulations ("Sims"):
These are all available at http://phet.colorado.edu and should run on any up-to-date PC or Mac systems.

Essential Reading:

Thinkwell   Professor Pollock's *Thinkwell Physics I*, www.thinkwell.com.

Hewitt   Paul G. Hewitt, *Conceptual Physics*, Addison Wesley, 2005.

Hobson   Art Hobson, *Physics: Concepts and Connections*, Prentice

Hall, 2006.

March   Robert March, *Physics for Poets*, McGraw-Hill, 2002.

Recommended Reading:

Feynman   Feynman, Leighton, and Sands, *The Feynman Lectures on Physics*, Addison Wesley, 1963.

Cropper   William H. Cropper, *Great Physicists*, Oxford University Press, 2001.

Gleick   James Gleick, *Isaac Newton*, Vintage, 2003.

Lightman   Alan Lightman, *Great Ideas in Physics*, McGraw Hill, 2000.

Crease   Robert P. Crease, *The Prism and the Pendulum*, Random House, 2003.

Gonick   Larry Gonick and Art Huffman, *The Cartoon Guide to Physics*, Collins, 2005.

Lecture One
The Great Ideas of Classical Physics

The important thing is not to stop questioning.
—Albert Einstein

Scope: Physics is the study of the natural world, an experimental science that lies at the heart of all other sciences. It is an effort to make sense of the world at a fundamental level, to unify and describe observable physical phenomena. *Classical* refers to the pre-20th-century developments in physics, a reductionistic, "realist" approach that continues to be one of the most productive and powerful tools in understanding nature. We begin with a broad overview of the domain of classical physics: matter and energy, space and time, particles and waves, and forces and motion. This course will take a "quasi-historical" path, and our themes will focus on such questions as: How do we know? Why does it matter? How does it tie together? How can I make sense of the world?

Outline

I. What is physics?
   A. Physics is the study of the natural world, the physical world, but it goes beyond a simple description of nature. It is an experimental science that lies at the heart of all other experimental sciences. It is also an attempt to unify, to look for underlying essential principles that explain and predict the behavior of natural phenomena and technology.
      1. Physics is about matter and energy, space and time, particles and waves, and forces and motion. In this course, we will create operational definitions for these terms.
      2. We will distinguish physics from other physical sciences, such as chemistry, biology, geology, and astronomy, although naturally, we will see a good deal of overlap.
   B. All science is tied to physics, but physicists tend to focus on the basics, the underlying principles, the "rules of the game," and the players. It is, in this sense, the "simplest" of the sciences!
      1. In physics, we often idealize or simplify. We talk about *pointlike objects* or *frictionless surfaces*; we might even posit a spherical cow!
      2. These kinds of approximations are starting points, ways to help us understand and build to more complex and realistic situations.
   C. The *great ideas* of physics are the essential, fundamental principles that we will look at throughout this course.
      1. We can't just list these principles, because in some sense, every idea that we'll talk about has served as a great idea of physics.
      2. Further, what was a great idea in one period of history may have evolved into other great ideas and lost its original usefulness.
      3. In the end, we'll discover that the great ideas of physics are the deep ones.
   D. An example of a great idea of physics arose in the 1600s, that is, that the world can be understood through experimentation.
      1. Before this time, people often attempted to understand the world by philosophizing about it, rather than observing or measuring phenomena.
      2. The development of the *experimental method*, or the *scientific method*, changed the nature of investigation of natural phenomena and was one of the first great ideas of physics.
      3. The scientific method, simply put, is as follows: Observe the world, formulate hypotheses, test and refine them, then repeat the cycle, looking for deeper explanations and seeking consequences and links using mathematical tools.
      4. Mathematics is a tool to formalize logical consequences. In a sense, mathematics is about cause and effect, an expression of relationships.
      5. The goal and result of this kind of investigation is to weave a tapestry of consistent, generalized, interconnected knowledge, verified at every step by "asking nature."

E. A recurring theme for this course is: How do we know? How did we come to believe this?

II. What is *classical* physics?

A. The word *classical* refers to a subset of ways we think about and investigate the natural world, building on the philosophical principles of realism, determinism, and reductionism.

B. Classical physics refers to ideas developed from slightly before Newton (in the 1600s) to the end of the 19th century.

III. Why should we care about classical physics?

A. Classical physics touches on every aspect of the world we live in, even the light striking our eyes, the sounds we hear, and the texture of objects in the world.

B. Classical physics is extraordinarily well established and useful. It plays a role when you turn on the light in your kitchen and cook something in the microwave.

C. Further, classical physics helps explain and enhance the "magic" behind rainbows and other natural phenomena.

D. Physics is about sense-making; it's not just a collection of facts. It's about finding "a-ha" moments and tying ideas together. We will focus on deep conceptual ideas and their applications throughout this course.

1. In one sense, you already know physics. You live in the world, and you know how the world works. In this course, you'll learn to organize your thinking and make connections between ideas that seem disparate but have much in common.

2. Physics is hard in the sense that we tend to live comfortably with contradictions, inaccuracies, or unhelpful generalizations and "rules" about the world. One of our goals in this course will be to uncover and correct such errors in our thinking.

IV. Where are we heading in this course?

A. We will follow a quasi-historical approach, beginning with the ideas of Copernicus, Galileo, and Newton. From there, we will work our way forward in time, following the great discoveries of physics.

B. We will begin with a branch of classical physics called *mechanics*, the study of force, energy, and motion. This study is foundational to our understanding of other ideas in physics.

C. We will then build on this foundation as we look at the forces of nature—gravity, friction, electricity, and magnetism. We'll also investigate the consequences of these forces in such topics as optics and thermodynamics.

D. The ultimate goals of this course are to spark your curiosity, to help you recognize the connections in physics to your life, and to have you enjoy the process of making sense of the world.

Essential Computer Sim:

Throughout much of this course, I will recommend that you visit the PhET Web site (Physics Education Technology), developed by my education research colleagues at the University of Colorado. The site contains a large (and growing) collection of physics simulations, designed to be playful and of broad use. They teach concepts of physics in a variety of ways, by allowing you to interact, to modify, and to test ideas. Some of these simulations "make the invisible visible," showing a model to help you make sense of some complex phenomenon. I encourage you to play with these simulations, enjoy them, and see how they tie in to the concepts we discuss in each lecture. For this first lecture, go to phet.colorado.edu and play the game called Estimation. There's not so much physics (per se) to be learned with this one, but it may give you some potentially useful insights into *scaling laws* and *guesstimation*, both of which will be useful concepts throughout the course.

Essential Reading:

Thinkwell, "1: Welcome to Physics."

Hewitt, chapter 1.

Hobson, chapter 1.1.

March, Preface.

Recommended Reading:

Feynman, Leighton, and Sands, "The Feynman Lectures on Physics", Addison Wesley, 1963

Note: I will not explicitly list chapters in the *Feynman Lectures* from this point forward. I recommend them because they are insightful, creative, and classic lectures. They are also darned hard. Although designed for college freshmen, they are at a mathematically (and physically) very sophisticated level, so much so that I cannot comfortably recommend the reading for *everyone* (after the introductory chapters listed above). But if you are able to handle the math and want to push yourself, these lectures are a wonderful introduction to the real *details* of introductory physics. See the bibliography if you want other ideas for going a little further into the material than these lectures, but not as far as Feynman!

Questions to Consider:

1. How would you define *science*? How about the *scientific method*? Is the scientific method as well-defined and simple as we teach children in elementary school? Is it really *more* than a clear set of steps to follow?

2. Think of a specific example in your life in which you have believed something, then later changed your mind. What steps were involved in that change; what did it take to make you change your mind?

3. If you understand the physical origins of a rainbow, does it make the rainbow less beautiful or more beautiful? If you understand something about what a star is, how it is formed, and how it evolves, does that make gazing at the night sky less mysterious and wondrous or more so?

4. In what ways are biology or chemistry (or your favorite science) based in physics?

Lecture Two
Describing Motion—A Break from Aristotle

*The important thing in science is not so much to obtain new facts
as to discover new ways of thinking about them.*
—William Bragg

Scope: Greek natural philosophers made enormous progress 2000 years ago, indeed foreshadowing many of the great ideas of modern science. But they were missing some essential contemporary ideas, particularly, the nature of the scientific method. This is where we begin—first, with a brief description of some of Aristotle's ideas about motion and the nature of objects. We then leap ahead to Galileo, who challenged these ideas with one of the simplest yet most profound and beautiful experiments of all time—marbles rolling down an inclined plane! There is much to be learned from such a simple exploration: the role of experiment and measurement, the isolation and control of physical effects, the role of approximation and simplification in science, the need for operational definitions of physical quantities (for example, what we mean by *speed* and its connection to everyday usage), and the role and power of mathematics and abstraction in our understanding of nature.

Outline

I. Ancient Greek natural philosophy was, in many cases, quite advanced, but it lacked a consistent scientific method.

   A. As we know, Aristotle (384−322 B.C.E.) was influential in a number of fields of study, including religion, biology, and physical systems. From a modern standpoint, however, some of Aristotle's views can seem murky and confusing.

   B. For Aristotle, every physical object has a "natural place." For example, heavy objects tend toward the ground, and light objects tend to move upward. Heavenly objects are of some other nature entirely.

   C. Part of the problem with these particular ideas of Aristotle's was that he did not conduct experiments, and he did not carefully define the quantities or attributes he wanted to measure. It is essential to establish operational definitions for such terms as *motion* and *velocity*; operational definitions tell us how these quantities are measured.

   D. Returning to the idea of the natural state of objects, we might ask: What happens if we perturb the natural state? For example, if we push a cart, it will move forward before coming to rest. Aristotle would argue that the cart comes to rest because it's the nature of a cart to come to rest.

   E. In the very classic physics experiment of dropping a heavy object and a light object at the same time to see which hits the ground first, Aristotle would say that the heavier object would fall to the ground "faster" than the lighter one.

   F. When an object is in motion, Aristotle might ask: What keeps it in motion? This question may seem perfectly reasonable, but in the end, we shall see that it turns out to be an unproductive, even incorrect (or inappropriate) question.

II. The experiments of Galileo (1564−1642) in the late 1500s and early 1600s represent a change in the very nature of scientific investigation, modifying and clarifying ancient ideas.

   A. Although Galileo lived during the Renaissance, a time of radical change, the prevailing attitude was still that the wisdom of the ancients was profound and correct.

   B. Galileo's insights spanned a broad spectrum of physical questions, including time, motion, astronomy, even relativity.

   1. Galileo recognized the need to make careful measurements and to isolate the phenomenon under study.

   2. In thinking about motion, Galileo realized that the strength of gravity made it difficult to study the idea that heavy objects and light objects fall at different rates. He effectively *weakened* gravity by using the inclined plane to study this specific aspect of nature.

3. Galileo also knew that in studying motion, measurements of distance and time are essential. He measured time using a number of unique mechanisms, including his own heartbeat, a water clock, and strings laid across his inclined plane to produce musical notes as the marbles rolled down the track.

4. Thus, Galileo isolated the phenomenon under study, established careful standards for measurement, and ultimately, performed a mathematical analysis of his results.

C. With Galileo, *kinematics*, the study of moving objects, became established. Keep in mind that Galileo's work did not explain motion; it simply described it.

III. Galileo was not, of course, the first person to be suspicious of the idea that heavy objects and light objects fall at different rates. At this point, you, too, may be suspicious of this idea.

A. A simple experiment, dropping a pen and a piece of paper at the same time, shows that Aristotle's idea is not as "obvious" as it may seem.

B. Part of Galileo's achievement was to see that "complications," such as air resistance or gravity, need to be eliminated from the experiment and considered separately.

C. Galileo also realized that standards of measurement were required for distance, time, velocity, and acceleration. Today, we generally use the metric system of measurement in science.

D. Finally, Galileo used mathematics as a tool to relate measurements of time and distance. His approach made use of geometry and ratios, rather than algebra, but the concept was the same: speed = distance/time.

IV. Rolling objects down inclined planes leads to several significant new ideas.

A. For example, Galileo had to take into account the results of rolling objects down planes inclined at different angles. This, in turn, brought in the concept of *limit* to his experiments.

B. Galileo saw what we now know: All marbles (of different weight) travel down the same plane at the same rate if "complications" are eliminated. This observation enabled him to look at the concept of *speed*.

1. Galileo carefully defined speed as distance traveled divided by time taken.

2. This definition enables us to distinguish between *speed* and *acceleration*, which is the rate at which speed changes.

3. Galileo's definition of speed is almost second nature to us now. We can easily use the speedometer in a car to predict when we will arrive at a destination.

C. Obviously, Galileo challenged the Aristotelian status quo, and in the end, his simple experiments yielded significant insights into universal aspects of motion, inertia, and gravity.

Essential Computer Sim:

Go to http://phet.colorado.edu and play the Maze Game, which introduces the concepts of position, velocity, and acceleration in a kinesthetic sense. The control field is in the bottom right portion of the screen; the object you will manipulate is in the top portion. First, choose what variable you will control with your mouse: position (R), velocity (V), or acceleration (A). You will see an arrow on the screen; place your mouse at the tip of the arrow, and use that to manipulate the small ball to move it to the goal. Try all three controls (R, V, and A), and think about what is different each time, that is, how your mouse manipulates the object in different ways. Which is easiest for you? Why? Can you see the big difference between R (position control) and V (velocity control)?

You have to think *very carefully* about what is happening in the acceleration mode—it can be confusing at first. Play with the simulation, and keep in mind that your mouse is not controlling position or velocity; it's controlling acceleration. If you can make *sense* of this, you will have mastered a very difficult and important physics concept!

Essential Reading:

Thinkwell, "1: Measuring the World around Us."

Hewitt, start of chapter 2.

Hobson, chapters 3.1, 3.2.

March, start of chapter 1.

Recommended Reading:

Cropper, chapter 1.

Crease, chapter 2.

Gonick, start of chapter 1.

Questions to Consider:

1. Give three common examples of velocity units that you might be comfortable using or thinking about. Why do we have different units to measure the same thing, anyway?

2. Following up on the previous question, think about defining standards for measuring things. If you lived in the Middle Ages, how might you go about defining a unit of distance? Of time? Of speed? Be sure to think about such criteria as accessibility (for ease of comparison), invariance (standards that don't change over time), and reproducibility. Are there other important criteria? Are the three I've listed all equally needed or desirable?

3. Galileo "slowed down" the effect of gravity by rolling marbles down ramps, instead of dropping them straight down. What if, instead, he had dropped them straight down through a jar of molasses? (That would have slowed them down also!) What would Aristotle have to say about that experiment? Would it work just fine and yield many of the same physical and scientific insights, or would it be flawed? Why?

4. How could you measure a time that is much shorter than a heartbeat (such as the time it takes a fly to flap its wing)? How could you measure a time longer than your lifetime (such as the age of the Sun)? How could you measure a distance shorter than you can focus on (such as the size of the eyeball of that fly)? How could you measure a distance larger than human scale (such as the distance to the Sun)?

5. What exactly do we mean when we say a marble is "speeding up" as it rolls down a ramp? How would you measure this? (It might help to think about a related question: How does a car's speedometer work? What is it really measuring?)

6. Try out the Galilean "ball drop" experiment for yourself. As a first goal, just try to convince yourself that (in the absence of drag) heavy and light objects fall at the same rate. Start with a piece of paper and a book (one that you won't damage). Does putting the paper under the book teach you something about falling objects? How about putting the paper on top of the book? How about crumpling up the paper?

Lecture Three
Describing Ever More Complex Motion

Familiar things happen, and mankind does not bother about them. It requires a very unusual mind to undertake the analysis of the obvious.
—Alfred North Whitehead

Every scientific truth goes through three states: first, people say it conflicts with the Bible; next, they say it has been discovered before; lastly, they say they always believed it.
—Louis Agassiz

Scope: Pursuing "marbles running down ramps" is a lovely, deceptively simple exercise, which leads us to insights beyond measurement, into the concepts of, and distinctions between, velocity and acceleration. Acceleration is a particularly subtle idea, but one of the paradigmatic ideas in physics, relating to the concept of *rate of change* of something. We will see how kinematics (the description of motion) allows us to make quantitative predictions about the future (and deductions about the past) and, ultimately, how it guides us toward the idea of inertia and the early classical ideas of the nature and dynamics of motion.

Outline

I. The results of Galileo's experiments led to the establishment of basic and productive principles for both science in general and kinematics in particular.

   A. Recall that kinematics is the description of motion. We'll begin this lecture by trying to define some of the terms we've used in talking about kinematics—*speed*, *velocity*, and *acceleration*. We'll also see that once we understand kinematics, we can begin to make predictions.

   B. *Speed* is distance traveled per amount of time taken.
   1. Average speed is *distance divided by time*, using any length of time chosen. The average speed is what you care about if you're driving to a destination and you want to know overall time and distance.
   2. Think of what *60 miles per hour* means. It's also 1 mile per minute, or 88 feet per second, or 27 meters per second.
   3. If you're traveling at a steady 60 miles per hour, you know exactly where you will be in 2 hours. This is how kinematics allows us to predict the future.
   4. Distance divided by time is a ratio—don't think of it as a formula into which we plug numbers. This ratio is what *speed* is.

   C. What is *instantaneous speed*, and how is it measured?
   1. Instantaneous speed is how fast you're traveling right now. It's what the police officer cares about when he gives you a ticket. If you say, "But, officer, my average speed for this trip was well below the speed limit," you'll still get a ticket.
   2. *Average speed* is relatively easy to define operationally, but *instantaneous speed* is a bit trickier. It implies a limit of averaging speed over an arbitrarily short time interval.
   3. A car speedometer computes average speed over such a short time (one wheel revolution) that it might as well be instantaneous.

   D. *Acceleration* involves the rate of change of speed. How rapidly is your speed increasing?
   1. Think of the difference between a sports car and an old microbus, each trying to get onto a highway at 60 miles per hour. The sports car takes 3 seconds to reach highway speed, but the microbus takes 60 seconds.
   2. The distinction between *speed* and *rate of change of speed* is subtle but critically important.
   3. When you stop your car, the change of speed may be the same, but the rate of change makes all the difference in the world.
   4. Acceleration is measured with curious units, for instance, *miles per hour per second*. In the sports car, our speed changed from 0 to 60 (a change in speed of 60 miles per hour), and it took the car 3 seconds to make that change. Thus, the rate of acceleration is 20 miles per hour per second ($60 \div 3$).

5. If I'm riding a motorcycle and I say, "My motorcycle has a huge acceleration right now," you can't tell me whether I'm going fast or slow.
6. If I'm on a bicycle, traveling at 20 miles per hour, I may touch my brakes gently and cruise to a stop in 20 seconds. Alternatively, if I run into a parked car, my speed will change from 20 miles per hour to 0 in a millisecond. In that case, my rate of acceleration is $-20,000$ miles per hour per second

$$\left(\frac{-20}{\frac{1}{1,000} \text{ of a second}} \right).$$

E. The Aristotelian language (*fast* or *slow*) is inadequate to correctly describe marbles on a ramp. Galileo observed that all marbles accelerate at the same rate.
   1. The speed gets faster and faster, but the acceleration is constant, given a particular incline.
   2. The acceleration will be higher if the ramp is steeper. We don't ask: How fast? or What's the speed for a given ramp angle? Instead, we ask: What's the rate of change of speed for a given ramp angle?

F. Language matters, and physicists use English-language words, such as *velocity*, *speed*, or *acceleration*, with care and precision.
   1. The concept (and mathematics) of acceleration allows us to make quantitative predictions (before or after an event) of speed at various times, without having to directly observe the event.
   2. The police are very good at using kinematics to make quantitative predictions, such as how fast a car was going *before* an accident.

II. What happens when we add an up ramp on the other side of the down ramp in the marble experiment? How high will the marble reach on the up ramp?

A. The marble will reach almost the same height at which it started. In fact, in this experiment, the details are not important, and in particular, the angles don't have to be the same. If the uphill is shallower, the marble will travel much farther, slowing down with a smaller acceleration but ultimately still reaching the original height.

B. With this experiment, we seem to be onto something a little deeper than just a description of motion.

C. Now consider the thought experiment of a perfectly flat "uphill."
   1. The marble will roll forever, "trying" to reach its original height.
   2. Only friction slows the marble down, but left to its own devices, the marble would continue to move in a straight line forever, at constant velocity.

III. The *principle of inertia* moves us beyond simple kinematics, to a broader concept of the nature of motion. This is the start of *dynamics*, the *explanation* of motion.

A. The principle of inertia states that an object in motion will remain in motion in the absence of forces.

B. Aristotle had no clear sense of this idea; his conceptions were contradictory to it.
   1. Aristotle's ideas about kinematics were not subject to experimental verification.
   2. Galileo is hinting that motion of all objects may be seen as universal, simple, regular, and predictable.
   3. He recognizes that you don't need to continually push an object; an object in motion will naturally continue in motion.

C. The ideas arising from marbles might be extended to other situations, including those involving baseballs, rocket ships, even planets orbiting the Sun. One need no longer invoke mystical reasons for why planets continue in their orbits; the inertia principle changes the story by changing the question.

IV. Before we close this lecture, let's briefly distinguish between the terms *speed* and *velocity*.

A. In everyday use, the two terms are synonymous.

B. In physics, *velocity* involves not just the speed but the direction of motion, as well.

C. Galileo's principle of inertia says that any object in motion, absent other forces, will have a constant velocity, that is, the same speed and direction, forever.

D. This point is critical in understanding circular motion, as we will see in future lectures.

Essential Computer Sim:

Go to http://phet.colorado.edu, and play with the Moving Man (and, optionally, Vector Addition.)

The Moving Man lets you further explore the ideas of position, velocity, and acceleration. Here, you move the character, and you see graphical representations of these three quantities. Drag the Moving Man, and look first at the position graph alone. Try to make sense of the visual representation. This one should be the most direct and the easiest to visualize. Next, focus on the velocity graph. Can you see the connection between the graph and the Moving Man's motion? The toughest idea is acceleration, as usual. Try this: Instead of dragging the man, you can also drag the sliders on the left side of the graphs; that is, you can set the position, velocity, and acceleration, then let the man go. What happens if you start off with a positive acceleration and let the man go from a state of rest? What if he starts with a negative (leftward) velocity but a positive acceleration? Play around! Once again, the idea of acceleration is subtle but important. If you can set the dials and *predict* what the qualitative motion will look like, you're making great progress in making sense of this idea.

The Vector Addition sim is for those who are interested in going a little further into the mathematics and representations of physics. Vectors represent many physical quantities, including velocity, force, momentum, and others. We will talk about "adding" vectors in this course, and this sim allows you to see, graphically, how one goes about doing that. It's not nearly so critical to understand, but if you make sense of this, some of the deeper consequences of Newton's laws will be easier to grasp in later lectures.

Essential Reading:

Thinkwell, "1: The Basics of Vectors" and "2: Investigating 1-Dimensional Motion."

Hewitt, rest of chapter 2.

Hobson, rest of chapter 3.

March, rest of chapter 1.

Recommended Reading:

Crease, chapter 3.

Gonick, rest of chapter 1.

Questions to Consider:

1. Velocity and acceleration are different things. Think of an example of an object with non-zero velocity but zero acceleration at the same moment. What about an object with zero velocity but non-zero acceleration at the same moment?

2. What is the difference between the Aristotelian and Galilean views of the "natural state of motion" of objects?

3. How does the English-language use of the term *inertia* (relating to human sluggishness) connect to the physics use of this term?

4. Galileo observed that the acceleration due to gravity is a constant, irrespective of mass. Does acceleration of any object rolling down a ramp have to be a constant in all circumstances? (What role does friction play?) Moving beyond marbles on ramps, what are some examples of objects that do not have a constant acceleration?

5. Why does a marble in a toy wagon appear to roll *backwards* when you give the wagon a sharp pull forwards? Is it, in fact, rolling backwards? (With respect to what?) Try it, watch carefully!

6. Think about making the Galilean ball drop more quantitatively. What measurements could you make (in the real world, such as in your living room!) that would convince you that dropped objects are falling "faster and faster," yet the rate of acceleration is constant? Hint: If you carefully time the fall from different heights, do you expect the total time to be proportional to the height? That is, if you double the height, do you double the time? (Answer: No, that's what you would expect if objects fall with constant speed, not constant acceleration.)

Lecture Four
Astronomy as a Bridge to Modern Physics

I've studied all available charts of the planets and stars and none of them match the others. There are just as many measurements and methods as there are astronomers and all of them disagree. What's needed is a long term project with the aim of mapping the heavens conducted from a single location over a period of several years.
—Tycho Brahe, 1563 (age 17).

He was a scholar of Polish birth,
who stopped the Sun and moved the Earth.
—Polish adage regarding Copernicus

The scientific theory I like best is that the rings of Saturn are composed entirely of lost airline luggage.
—Mark Russell (political satirist)

Scope: The roots of physics and astronomy are closely tied. Questions of our place in the universe, the nature of planets, and the structure of the solar system were at the heart of the development of classical physics. Some ancient Greek philosophers argued for Sun-centered, round-Earth solar systems, but ultimately, the Aristotelian worldview, backed by the detailed model of Ptolemy, settled in and reigned. Copernicus re-proposed a heliocentric worldview, and the detailed data of Tycho Brahe, analyzed by Johannes Kepler, refined and improved that cosmology to something close to what we understand today. The attempts to make sense of these results, fitting together with the ideas of Galileo, ultimately led to Isaac Newton's articulation of the "laws of nature," which define the heart of classical physics.

Outline

I. Galileo's experiments occurred in a rich context; the world was changing in all fields—philosophy, politics, art—not just science. Our place in the universe was a big question of the day.

  A. Cosmology (the structure and origins of the universe) is a primal issue and central to the development of science.

  B. Every culture develops its own cosmology. People seek to explain the phenomena they see in the world around them.

  C. Today, astronomy is very much its own science, but in the time of Copernicus and Galileo, astronomy and physics were intimately coupled. Astronomy was also an early driving force for data collection.

  D. Greek natural philosophers had made great progress in the big questions of astronomy.
  1. What is the structure of our solar system?
  2. Is the Earth round or flat? The answer to this question was known (quantitatively) a long time before Columbus. Ask yourself: How would you decide such a thing? How could you determine the size of the Earth (with 2000-year-old technology, at that)?
  3. Is the Earth at the center of the solar system? Aristarchus (310–230 B.C.E.), a Greek mathematician and astronomer, postulated that the solar system was heliocentric.
  4. The answers to these questions are "obvious" to the casual observer (who is often wrong!). It is far from obvious that we are rushing through space or spinning. (Do you feel dizzy all the time?)

  E. Ptolemy (c. 85–165) created a model that quantitatively explains and predicts astronomical phenomena.
  1. A model is a representation of the world. It can be physical or mathematical, concrete or abstract. Models are a fundamental ingredient in physics; they are the ways in which we think about the world.
  2. Models, by necessity, miss features; they are simplified representations, and they may or may not be considered "real." They provide a way of thinking about, understanding, and predicting the behavior of more complex systems in the real world.
  3. Ptolemy's astronomical model involved imaginary spheres circling the Earth. In this model, the Sun and Moon circle the Earth directly.

4. The planets travel in circles around circles in orbits called *epicycles*. As time went by, Ptolemy's model grew more complex to match improved observational data.
5. This model was successful and compelling, despite the complexity of epicycles and imaginary spheres. It survived for 1000 years.

II. Copernicus (1473−1543) questioned the Ptolemaic model, leading to one of the first great scientific revolutions in history.

A. Copernicus's heliocentric model was simpler, in fact, too simple. He still subscribed to ancient wisdom, for example, the notion that astronomical objects are ideal and, hence, must follow perfectly circular paths.

B. Copernicus did not publish his work, *De revolutionibus*, until late in his life, in 1543, partly for fear of political and religious consequences.

C. The *Copernican revolution* was neither complete nor immediate, but Copernicus deeply influenced Galileo, whose astronomical observations led him to argue strongly for the heliocentric model, helping overturn long and deeply held traditions.
   1. Galileo's observations with the telescope revealed, for example, that Jupiter hosted a "mini" lunar system, similar to the larger solar system. This was a powerful challenge to the idea that the Earth was at the center of the solar system.
   2. Galileo also observed spots on the Sun and shadows on the Moon, leading to the heretical idea that the celestial bodies were not perfect.

III. Tycho Brahe and Johannes Kepler collected and analyzed astronomical data with unprecedented accuracy at the turn of the 17th century.

A. Tycho Brahe (1546−1601) was perhaps the first contemporary experimental astrophysicist; his work was complete with government-sponsored big science facilities and lasted over a period of 20 years in the late 1500s. His assistants made meticulous astronomical measurements using handheld devices.

B. Brahe had his own hybrid cosmology that would preserve significant Church beliefs. According to his model, the planets orbit the Sun, but the Sun and all the planets also orbit the Earth.

C. Johannes Kepler (1571−1630) was hired by Brahe in 1600; his mandate was to show that the data agreed with Brahe's model, but instead, he recognized that a much clearer description of the data was possible if Brahe's hypothesis was modified.
   1. Kepler's work is more "scientific" (by modern standards) than that of Copernicus.
   2. Kepler's first law of planetary motion stated that planetary orbits are ellipses, not perfect circles.
   3. His second law stated that, as planets orbit the Sun, they speed up and slow down in mathematically well defined (but, at the time, completely mysterious) ways.
   4. According to Kepler's third law, the time taken to orbit the Sun depends in a simple way on the planets' distance from the Sun.

IV. Kepler described the kinematics of planets, just as Galileo had described the kinematics of rolling marbles.

A. Galileo's insights into acceleration tie in to the description provided by Kepler.
   1. Again, *acceleration* is the rate of change of velocity—the change in velocity divided by the time taken.
   2. Thus, even if the planets travel in perfect circles at constant speed, they are accelerating because their velocity (direction) is changing.

B. Galileo's observations of the phases of Venus served as strong support for Kepler's model of the solar system. The Ptolemaic model would be unable to account for the fact that Venus had phases, just as our Moon does.

C. Questions still remained, however: If the Earth is spinning, why don't we feel dizzy? Why doesn't the Earth fly away from the Sun? The stage was set for a profound scientific revolution, but it required the genius of Isaac Newton to provide the framework in the form of the scientific method, measurements, mathematics, physical theory, and "laws" of nature involving kinematics, force, and gravity, to pull the story together into an elegant and compelling whole.

Essential Computer Sim:

Go to http://phet.colorado.edu. To help understand question 3 below, play with the 2D ("two-dimensional") Motion sim. This simulation lets you watch an object moving in circles (and other paths) and examine the velocity and acceleration. Click on the Circular Motion button, then look at the velocity and acceleration arrows. The velocity arrow will probably make sense to you, but the acceleration arrow is harder to grasp. You might go back to the Maze Game and play around in the acceleration control mode again. How do you make an object go in a circle? The fundamental question is as follows: If you are walking in a circle, you are constantly changing the direction of your velocity. Which direction is the *change*? (*Change* is defined as the difference between final and initial values. Alternatively, change is what you have to add to the starting value to end up at the final value.) The direction of acceleration for an object moving steadily in a circle is always directly toward the center of that circle. This is a tough concept, and without math, we're a little handicapped in understanding it. Just think about it! If you still don't quite get it, it won't matter much as we move on, but it is a very cool concept to grasp.

Recommended Computer Sim:

This sim comes from the University of British Columbia and is more directly related to Kepler's laws and planetary orbits. Go to http://www.cecm.sfu.ca/~scharein/astro/.

1. Start with the link labeled Phases of the Inner Planets. What are the observational differences between the Ptolemaic and Copernican models? (Telescopes were first used for astronomical observations in the early 1600s and obviously had a big impact on the acceptance of the Copernican model.)

2. Next, go to the Retrograde Motion sim. Click the Trace On button to clearly see the planets' motion. Which two planets are included in this model? This simulation explains why the Greeks called planets "wanderers." Sometimes these special "stars" would move in the wrong direction against the background stars. It was this motion that compelled astronomers, including Ptolemy, to construct elaborate models to explain such curious observations.

3. Finally, try the Kepler's Laws sim. Notice that after a planet starts orbiting, an orange wedge appears. This wedge represents the area the planet has swept out in a given time. Even as the wedge changes shape, its area is always a constant. (This demonstrates the second of Kepler's laws: a geometrical explanation of the fact that planets move faster when closer to the Sun.) If you exaggerate the elliptical nature of the orbit, this effect is more obvious. The screen also presents data on the *period* and *semi-major axis* (that's basically the average distance to the Sun, the effective "radius" of the orbit) in the upper left-hand corner. Can you discover the quantitative relationship between these two numbers, a pattern that allows you to *predict* the period for planets at an arbitrary radius? (If not, don't feel bad. Kepler was an extraordinary mathematician and "pattern finder.")

Essential Reading:

Thinkwell, "7: Orbital Motion" (first two segments).

Hobson, chapter 1.

March, start of chapter 4.

Recommended Reading:

Crease, chapter 1.

Gonick, chapters 2–5 span this and the next several lectures.

Questions to Consider:

How "sky aware" are you? What's the current phase of the moon? If it has been awhile since you've done so, find a night to get away from city lights and just watch the starry night sky!

1. Think about how you would measure the radius of the Earth if you had access only to tools and technology available 2000 years ago. How about the distance from the Earth to the Moon? From the Earth to the Sun?

2. How would you convince a contemporary skeptic that the Earth is *not* flat or that the Earth is not the center of the solar system? Would you have sided with Copernicus if you read *De revolutionibus* in the late 1500s (after his death but before the invention of the telescope and, particularly, before Kepler's careful analysis of the data on planetary motion)?

3. In what ways is Copernicus's heliocentric model of the solar system better than the ancient Ptolemaic model? In what ways is it *worse*?

4. I stated that an object moving in a perfect circle, *at a steady speed*, is accelerating. How can something accelerate if it goes at a steady speed? Can you make sense of this? If you drive your car in a tight circle at steady speed, does it *feel* like you are accelerating? (Recall that *acceleration* is defined as the rate of change of velocity, not the rate of change of speed. *Velocity* describes your speed *and* the direction you are going.)

Lecture Five
Isaac Newton—The Dawn of Classical Physics

Plato is my friend, Aristotle is my friend, but my best friend is truth.
—Isaac Newton, from his early college notebook

Scope: The historical turning point in the development of physics, the "dawn of classical physics" is easily located—it belongs to one man, Isaac Newton. Newton's story is fascinating; he was an intense, lone character who single-handedly developed calculus, laws of motion, gravity, optics, and more, including his articulation of the scientific method in his *Principia*. We will look at the origins and development of Newton and his ideas and zoom in on the first two of his laws of motion, involving inertia (mass), acceleration, and force.

Outline

I. Isaac Newton is so deeply tied to classical physics that he almost defines it.
   A. Isaac Newton was born in 1643, the year Galileo died, on a small farm in England. His father died before he was born, and his family was not particularly wealthy.
   B. As a boy, Newton was a decent student, and he began to really stand out in his teens.
   C. He was sent to Trinity College (a religious institution), where he studied philosophy, including natural philosophy, and mathematics.
      1. Newton was socially isolated and unhappy; as an adult, he was rather unpleasant, not a "nice guy."
      2. He was partly self-taught, with a deep interest, even as a child, in natural phenomena. As a boy, he built sundials, model windmills, and kites on his own.
      3. His early notebook indicated amazing insight into the big questions about the natural world, ranging from light and sound to fluids, gravity, astronomy, and much more.
   D. In 1665, at the age of 22, Newton returned to the family farm because of an outbreak of the plague. In less than two years, his genius blossomed, and he produced the core of physical and mathematical insights to which he would return throughout his professional life.
      1. This is the period of the (apocryphal) story of a falling apple providing the flash of insight into the universal nature of gravity
      2. Newton knew of Kepler's discoveries and worked on deep astronomical questions.
      3. Because algebra and geometry were too limited to solve the astronomical and physical problems involving changing quantities that Newton was working on, he invented the calculus to help.
      4. The *Principia*, containing many of the ideas Newton developed during this time, was not published until 1687. Newton's ego and personality were not conducive to sharing his work, but he was badgered into publishing by Edmond Halley (of comet fame).
      5. The *Principia* is perhaps the greatest, most influential single publication in the history of science. It is a rich treatise of Newton's new physics and its application to astronomy, including his law of gravity, his investigations into optics, and his articulation of the scientific method.
   E. As mentioned, Newton was apparently not a nice man—suspicious, quick to anger, jealous, and erratic. He mistreated contemporaries, including Robert Hooke and, later, Gottfried Wilhelm Leibniz, the "other" inventor of calculus.

II. Some of the fundamental ideas that Newton developed, particularly his laws of motion, form the basis for much of classical physics.
   A. Newton's first law (N-I) the law of inertia, states: If there are no outside forces (or if outside forces cancel out), an object at rest remains at rest; an object in motion remains in motion (in the same direction with the same speed) indefinitely.
   B. In formulating this law, Newton elaborated on and clarified ideas produced by Galileo and others.
   C. Newton's first law ties in closely to the concept of *frame of reference*; this is defined, essentially, as one's position as an observer.

1. You and I may have two different frames of reference, and we may agree or disagree in our observations of the same phenomenon.
2. For example, if we both observe a marble rolling across a table from different positions, we might agree that the marble is moving at a rate of 2 meters per second.
3. However, if you are observing the marble while you travel parallel to it on a rolling cart, you might observe that the marble is at rest as you move along beside it.
4. This idea builds on Galileo's principle of relativity, which tells us that although different observers may choose different ways to describe motion (some things are relative), the principles of physics themselves are invariant.

III. Newton's second law (N-II) addresses the question: What causes a change in motion of an object? The answer is the application of a force.
   A. Newton's law is written $F = ma$, that is, force equals mass times acceleration; it relates the force on an object to the inertia (mass) of the object and the resulting acceleration.
   B. Let's look at the three common English words in this equation: *force*, *mass*, and *acceleration*.
      1. Again, we must be careful not to confuse common English uses of these words with the physicist's carefully constructed operational definitions.
      2. To a physicist, *force* means push or pull, and it is measured quantitatively, for example, with a spring scale. The unit of measurement for force is a metric unit called the *newton*; 1 newton of force is a gentle push. In the English system of measurement, force is measured in pounds.
      3. Forces refer to the interactions of objects. Forces can be applied by living beings or inanimate objects.
      4. Examples of forces include the gravitational force, the contact force of a chair holding you up, the tug of a rope, and the push of a stretched spring.
   C. *Mass* is part of Newton's law of inertia. In everyday English, *inertia* means sluggishness, resistance to change. In a similar vein, all material objects have a certain resistance to change in motion. Thus, mass is a quantitative measure of an object's inertia. In the metric system, mass is measured in kilograms.
   D. As we've said, *acceleration* is a description of motion; it tells us the rate of change of velocity.
   E. N-II, then, tells us what the resulting acceleration of an object will be as a result of the application of a force.
   F. N-II is about cause and effect: Force is the cause, and acceleration is the effect. Mass is a relevant number that tells us how these two factors are related.
   G. Kinematics described motion, but N-II helps us explain, predict, and control motion.

IV. Along with Newton's third law (N-III) and the law of gravity (which we'll get to soon), these deceptively simple relations form the heart of classical physics.
   A. The force concept is rich and deep. It takes practice to master the subtleties! We will return to it in the next lecture and beyond.
   B. Newton's laws are the basis for a simple, mechanical, deterministic, and quantitative description of a vast array of observable phenomena.
   C. Newton single-handedly changed the world, and we'll spend much of the rest of this course tackling the amazing ideas he came up with.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Forces in 1D. Try to make sense of the various graphs. Can you connect what's happening to the object to what's being plotted? (Use the slider on the left of the force graph to apply a force, rather than applying the force on the object itself.) Go to More Controls to turn off friction and see how that influences the simulation. Can you verify the rule that states, "If there is no net force, the velocity is constant," even when there *is* friction?

Essential Reading:
Thinkwell, "1: Rel Motion/Ref Frames," "3: Dynamics, Newton's Three Laws" (first two parts).
Hewitt, start of chapter 4.

Hobson, start of chapter 4.

March, start of chapter 3.

Recommended Reading:

Cropper, chapter 2.

Gleick.

Gonick, chapters 6-7 span this and the next several lectures.

Questions to Consider:

1. Why would the idea of "universal gravity" (acting on an apple or the Moon) be so radical in Newton's time? Is it obvious? What does this tell you about the scientific worldview regarding gravity and planets before Newton?

2. If you are in the space shuttle and a heavy metal object is loose and floating past you, will it be very easy to move around because it's "weightless"?

3. How are mass, inertia, and weight related to one another? How are they different? Do kilograms and pounds measure exactly the same thing? If not, what's the fundamental difference?

4. Surface gravity on the Moon is about 1/6 of what it is here on the Earth. If you go to the Moon, what happens to your weight? What happens to your mass?

5. Consider two observers in two different reference frames watching the same object, perhaps a box of books being pushed across the floor. What physical quantities will the two observers agree on, and what will they disagree about (mass, position, velocity, acceleration, force)?

6. If you're in shape to do so, go to a gym and put a comfortably heavy dumbbell in each hand With your arms down at your sides, do some squats, fairly quickly. (No knee injuries, please!) Note carefully how heavy the dumbbells *feel* as you initially push off the ground, as you ascend, as you stand to full height, as you descend, and as you reach the bottom of your squat. How does this fit in with $F = ma$?

Lecture Six

Newton Quantified—Force and Acceleration

*I understand what an equation means if I have a way of figuring
out the characteristics of its solution without solving it.*
—Paul Dirac

Scope: The one master equation for this course, and the heart of mechanics, is Newton's formal statement of this relationship between cause and effect, force and acceleration: force equals mass times acceleration, $F = ma$. This is the formula that determines almost all of classical physics. It's both simple and deep, and it's pretty tough to make sense of. To develop a "force concept," we will talk about thought experiments involving pushes and pulls, figure out how to quantify and visualize the three terms in Newton's law, and then consider the myriad ramifications. The law is quite universal—it can be used to predict, describe, and understand the motion of just about anything!

Outline

I. *Dynamics* involves the explanation, rather than simply the description, of motion.

    A. Newton, following Galileo, recognized the central question is not what keeps an object going but, instead, what makes its motion change.

        1. As we said in the last lecture, *force* is about push and pull.

        2. The equation $F = ma$ quantifies motion: If we apply a measured degree of force, we can calculate the acceleration, which tells us the rate of change in velocity. Knowing velocity over time enables us to predict where the object will be at a certain point.

        3. Newton's work leads to a new branch of physics—*dynamics*, which explains motion, rather than simply describing it.

    B. N-I and N-II are coupled and explain that inertia is the natural tendency of objects to remain in motion, while forces cause change. Specifically, force determines the rate of change of velocity.

    C. These laws, developed from (often simple) experiments, have been as well tested as any physical principle in history. Newton's laws are manifested everywhere in life, from driving cars to watching sports.

    D. However, we should also note that Newton's laws are technically wrong; e.g., Albert Einstein's theory of relativity tells us that we must modify how we think about mass and inertia when we are dealing with very large or very small scales.

    E. Most people struggle to make sense of Newton's laws.

        1. Think again of the Aristotelian cart. We know from Newton's laws that it stops moving because of a force (of friction).

        2. Part of Newton's genius (and Aristotle's failing), was recognizing that friction is just another force among many.

        3. It takes a lot of practice to look at a situation and articulate and delineate the various forces acting in that situation.

II. N-II ($F = ma$) tells many stories.

    A. Thought experiments help unpack the relationship and make sense of it.

        1. An air hockey table is a good example of an environment in which friction is reduced. Imagine that you have a puck attached to a weighted string resting on an air hockey table (hanging over an edge). You could easily watch the force of gravity pulling on the string and causing the puck to accelerate across the table.

        2. As you watch, you might see that the puck is accelerating at a constant rate of 1 meter per second per second (1 m/sec^2).

        3. What if you pull on the string twice as hard? You'll note that the puck accelerates at a constant rate of 2 meters per second per second. You have doubled the acceleration because you've doubled the force.

        4. What if you double the mass of the puck by stacking another one on top of it? The puck will accelerate half as rapidly.

B. Part of our confusion involving Newton's laws is that we are not kinesthetically aware of all the forces that are at work. In this situation, as you pull the string, the puck, not you, experiences the friction.

   1. If you're pushing a box of books across the floor, you're aware of the force that you're applying, but you're not directly aware of the frictional force of the ground pushing backward on the box.

   2. If the two forces acting on the box cancel each other completely, then there is no net force on the box and, thus, no acceleration.

   3. Knowledge of N-II helps us to become more aware, even kinesthetically, of the forces present in the world.

   4. Physics is *not* counterintuitive, but we do have to think clearly and carefully about what we believe we know.

C. Let's return to the idea of net (or total) force.

   1. Consider Galileo's cannonball dropped from the Tower of Pisa. After the cannonball is let go, it is acted on by only one force (gravity—the *weight* of the object) and, thus, accelerates down.

   2. Before the ball is dropped, it is acted on by two forces—the downward force of gravity and the upward *contact* force from the hand holding it. These two forces combine and cancel each other out. With no net force, the object at rest—the cannonball—remains at rest.

   3. When the hand lets go of the cannonball, only one force—gravity—is acting; thus, the ball will accelerate downward.

   4. On the way down, air resistance will build up. This is another force, which points upward, opposing the motion. The net force while falling, then, is weight (pulling downward) and air resistance (pushing up). These will *partly* cancel, but for ordinary objects, the weight dominates, and the object still accelerates downward.

III. The equation *F = ma* is a relationship, an expression of cause and effect. There are many points to make to fully understand this relationship.

A. The equation is not a definition or tautology. Each of the terms can be independently measured, determined, and defined.

   1. Force is measured in newtons. A newton is about 1/5 of a pound, what you feel in your palm when you hold a big apple.

   2. Mass is measured in kilograms; the American unit—the slug—is almost never used.

   3. Acceleration is measured in meters per second per second. That's not a typo—it tells you how much faster you go (in m/sec) every second. It's the rate of change of your velocity.

B. N-II is not just a "good idea." It's one of the fundamental laws of nature. The "big deal" is that it predicts and describes everything—it's universal. It's a part of engineering, of all the sciences, and of our lives.

C. Force has a direction, which tells us the direction of acceleration; mathematically, we call it a *vector*.

   1. Picture force as an arrow. It has a magnitude (how strong the push or pull is) and a direction.

   2. We can also picture velocity as an arrow; it, too, has a magnitude (length) and a direction. The force arrow and the velocity arrow are different; one doesn't tell you the other. Force doesn't cause velocity; it causes the change in velocity.

   3. Finally, picture acceleration as a third arrow. The magnitude tells you how rapidly the velocity is changing, and the direction tells you which way the velocity is changing.

   4. The direction of the force tells you the direction of the acceleration. They're the same direction; that's N-II.

   5. Mass has no direction; it's just a number. Mass does not point down; it's the force of gravity acting on mass that does so.

D. For most people, the idea that applying more force causes more acceleration is intuitive, as is the idea that the greater the mass of an object, the less acceleration will result from application of a force.

E. We can use the equation in both directions: Force predicts acceleration, but acceleration can be observed to deduce forces. Think of all the possible applications.

   1. We can successfully design roads to keep cars safely accelerating through a curve, steer rockets to Mars, or guide electrons through a circuit in a computer.

   2. We can determine "invisible" forces by watching their influence on subatomic particles or stars in the galaxy.

Essential Computer Sim:

Go to http://phet.colorado.edu and again play with Forces in 1D. Can you investigate and verify N-II ($F = ma$) with the sim? What happens if you double the net force? What happens if you double the mass? What happens when you add friction? Can you verify that it is the total force, not just your applied force, that matters? Also check out the Ramp to see if you can start to put together the vector nature of forces. Keep in mind, once again, it is only the total force (the "arrow" that arises from adding all the individual forces) that matters.

Essential Reading:

Thinkwell, rest of "6: Dynamics, Newton's Three Laws."

Hewitt, rest of chapter 4.

Hobson, middle of chapter 4.

March, rest of chapter 3.

Recommended Reading:

Gleick.

Gonick, chapters 2–7 continue to span this material.

Questions to Consider:
1. Use Newton's laws to explain how and why seatbelts and air bags work. Why do they help protect you?
2. Does a body always move in the direction of the net force on it? Why or why not?
3. After a rocket is launched, its velocity and acceleration increase with time as the rocket engines continue to fire, even if they are exerting a steady (constant) thrust (force). Can you explain how and why both velocity and acceleration continue to increase? (The former is not so hard; the latter is a little subtler.)
4. It takes a lot of force on the pedals to get a bike moving up to speed, but much less to coast along at constant speed. Why is that? When the bike is coasting along the flats, you do have to apply a little force to keep a constant speed. But Newton says that if your velocity is constant, there is zero net force. How can you make sense of this?
5. If you are in an elevator that accelerates up, you will feel a little heavier than usual. If the elevator is accelerating down, you feel a little lighter than usual. Try to use Newton's law to make sense of these physical sensations.

Lecture Seven
Newton and the Connections to Astronomy

It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.
—Richard Feynman

Scope: Applying N-II ($F = ma$) in real-life situations requires a lot of finesse, but it provides a framework for making sense of a vast variety of phenomena. Thinking about circular motion led Newton directly to a qualitative and quantitative understanding of planetary motion, closing the loop with Galileo, Kepler, and Copernicus and making sense of a Sun-centered solar system and its connection to everyday motion. In the process, Newton forever changed our views on our place in the universe and the structure of physical laws.

Outline

I. Let's begin with a quick recap of Newton's first two laws.

    A. The first is the law of inertia: In the absence of an external net force, an object in motion will remain in motion at a constant velocity forever.

    B. The second law, $F = ma$, quantifies the notion of inertia; it tells us how pushes and pulls affect motion.

II. Let's think about the connections with gravity, leading us back (in the end) to central questions of astronomy and the solar system.

    A. The force of gravity on an object, called its *weight*, depends on the mass, but it is not the same as the mass.

        1. Light objects have less "stuff" in them, and correspondingly, the tug of gravity on them is less.

        2. An anvil in the space station would have the same mass that it does on the Earth. It would be just as hard to accelerate the anvil in space. (Its weight is another question, to which we will return.)

    B. Near the Earth, the force of gravity is proportional to mass. Combining this fact with N-II leads to a stunning conclusion: All objects in freefall accelerate at the same rate.

        1. Galileo discovered this empirically, but Newton provides a simple and clear explanation of this phenomenon.

        2. To understand Newton's explanation, let's rewrite $F = ma$ to read: $a = F/m$.

        3. Now think about the solid cannonball being dropped off the Tower of Pisa. It may have 10 times the mass of a hollow cannonball, but it also has 10 times the weight. Thus, the force of gravity on that massive object is 10 times greater. The mass and the force cancel each other. The result? Both the solid and the hollow cannonball (in fact, all objects feeling only gravity) accelerate at the same rate.

        4. Near the Earth, all objects accelerate by 9.8 m/sec each second (10 m/sec is very roughly 20 miles/hr, or 32 ft/sec). Think about what this means—every second, you go 10 m/sec faster than you were going before.

        5. If we take into account air resistance, this story changes slightly, but gravity still dominates.

III. What happens when gravity acts on an object that is already moving? If I tossed my key ring, for example, we all know that it would follow an arc as it fell to the ground.

    A. Galileo recognized the *principle of superposition* in such a situation: Sideways motion and vertical motion are independent. N-II ($F = ma$) can be applied *separately* to both "aspects" of motion.

    B. Without gravity, a sideways moving object continues moving sideways forever.

    C. With gravity, an ever-increasing downward motion is added.

        1. According to $F = ma$, a downward force causes a downward acceleration.

        2. The sideways "component" of the motion continues unaffected.

        3. *Superposing* these two effects, the resulting path is a lovely and simple parabolic arc.

IV. What does it take to make an object go in a circle?

    A. If you are walking in a circle, even if your speed is never changing, circular motion most definitely implies that you are accelerating.

1. Picture walking in a circle. Let your hand point ahead, in the direction of your instantaneous velocity. Imagine watching from above—your hand points in different directions all the time. Your velocity is always changing (direction)!
2. Which way is it changing? To walk in a circle, every step you take, you need to go a little toward the center of the circle; otherwise, you'll follow a straight line and go away from the center.

    B. You need a force to accelerate. An object will not naturally go in a circle unless there is a force on it.
1. The equation $F = ma$ applies to any kind of motion. If the object is going in a circle, an inward force must be applied, pointing toward the center of the circle.
2. A "center-seeking" force is called a *centripetal force*. (*Centrifugal force*, in contrast, is the sense of being thrown outward when you are moving in a circle in a non-inertial, or accelerating, reference frame.)

V. Newton's grand insight was that gravity is a universal force that applies as much to the Moon, Earth, and Sun as to apples. The same law of motion for terrestrial objects explains celestial motion.

    A. Why does an apple fall? Because of gravity. How high, then, does gravity reach?
1. Even climbers at the top of Mt. Everest feel gravity; it clearly reaches up as high as any terrestrial places.
2. Newton asked: What if it reaches all the way up to the Moon and beyond? The answer was his "aha!" moment. Gravity must be the reason that the Moon circles around the Earth, rather than traveling in a straight line (and leaving us).

    B. Gravity is universal, and there is nothing inherently mystical about the Moon, planets, or stars. Their behavior follows Newton's laws just as Galileo's marbles or any other objects do.

    C. If gravity pulls on the Moon, why doesn't it fall toward the Earth?
1. It does! Remember, when you walk in a circle, your velocity is changing; you are accelerating toward the center. If you did not, you would walk away in a line.
2. The sideways velocity of the Moon is unaffected by gravity, so it does not change. As the Moon falls toward the Earth, it is also moving to the side because of its sideways speed. This is precisely what yields a circular (or elliptical) path for the Moon.

    D. Newton's laws unify very disparate realms of investigation.
1. Kepler formulated three laws of planetary motion: All planets move in ellipses; they speed up and slow down; and the distance of a planet from the Sun tells us its average speed. Newton saw that these observations arise mathematically from $F = ma$.
2. Newton's insight connected Galileo's marble on a ramp to an apple falling straight down out of a tree and to the Moon in orbit.
3. You can see this insight another way if you think about a toy on the end of a rope that you might swing around your head before letting it fly. The toy on the end of the rope is traveling in a circle because the rope is pulling it inward. As you swing the rope, you are also giving the toy a sideways motion. When you let go, you will see the toy continue in a sideways motion until gravity pulls it down.
4. Newton's laws are quantitative. We can derive the numerical values for the acceleration and check that they match the astronomical data.
5. The scientific worldview provided by Newton is, in a sense, complete: We can use it to describe microscopic and macroscopic phenomena (subject only to the subtle modifications of relativity and quantum mechanics).
6. In the next lecture, we'll talk about one more key piece to the gravity story: How does gravity depend on distance?

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Projectile Motion and 2D Motion. Projectile Motion gives a sense for the motion of an object with a constant downward acceleration. Can you make measurements to see for yourself that "sideways motion" is constant, even though "up-and-down motion" steadily accelerates downward? Does the path, and changing speed, make sense to you, based on Newton's laws? You may have already looked at 2D Motion, but look again, and see how the direction of acceleration for an object moving in a circle matches up perfectly with the

direction of the force of gravity. This is one of the subtler points of this lecture: Moving in a circle with constant speed means that your acceleration is directly toward the center of the circle. Convince yourself that this is correct and makes sense, rather than just taking my word for it!

Essential Reading:

Hewitt, start of chapter 8.

Hobson, start of chapter 5.

March, start of chapter 4.

Thinkwell, "2: Uniform Circular Motion," "3: Dynamics of Circular Motion," and "7: Orbital Motion" (again, if you need it).

Recommended Reading:

Gonick, chapters 2–7 continue to span this material.

Questions to Consider:

1. If you drop two identical bricks side by side, nobody has any difficulty imagining they will accelerate at the same rate. But some people still struggle with the idea that a brick "twice as big" won't accelerate faster. Imagine that the two bricks are dropped right next to each other. Does that make any difference? Would it make any difference if they had sticky sides? What if they were so close that, partway down, they touched and stuck to each other? Would that suddenly make them fall faster? What if they were stuck together the whole way down? Can you make more sense of *why* heavy and light objects fall at the same rate now?

2. Two objects fall freely. Their acceleration is the same. Does this mean that they must both have the same mass? Does it mean that they both feel the same force?

3. How is it possible for an object to be moving in one direction but accelerating in a different direction? Can you think of some examples? Could you possibly drive through a curved path without accelerating? (Think about your answer to this in two different ways. First, consider kinematics: Can you go around a curve without changing your velocity vector? Next, think about it from Newton's perspective: Can you navigate a curved path with zero force at any time?)

4. Is the speed of a struck baseball the same throughout its parabolic arc?

5. A friend who is not listening to these lectures insists that you are not accelerating if you drive around a curve at constant speed, because the speedometer remains steady. Refute this argument. (Can you do so in multiple ways?)

6. You fire a tranquilizer dart exactly horizontally out of a gun and, at the exact same moment, drop a second dart from a resting point at the same height as the dart gun. Neglecting air resistance, which one hits the ground first? (This may be surprising, but remember the principle that horizontal motion is independent of vertical motion.)

   You can set up a little "home experiment" to try this. The simplest setup is to place a ruler near the edge of a table and put one nickel on top of the ruler and a second nickel on the edge of the table in front of the ruler. Give the ruler a quick snap so that it strikes the nickel on the edge of the table and jerks out from underneath the other. The struck nickel goes flying (in a straight horizontal direction), and the nickel on top just falls from a resting point straight down. Listen carefully; they will hit the ground at the same time. Try it! The experiment may take some practice or variations to get it to work right. You need to be careful that: (1) both objects start to freefall at the same time and (2) neither object is given any *vertical* motion at the starting instant.

Lecture Eight

Universal Gravitation

Gravitation is not responsible for people falling in love.
—Albert Einstein

Scope: Newton's laws of motion needed to be combined with a law of gravitation in order to complete the job of predicting and understanding planetary motion. The deduction of the law of gravity involved some speculation, a little math, and a lot of creativity! In the end, the universal nature of gravity meant that Newton's worldview was simple and "complete"—unifying terrestrial and celestial phenomena into one framework. It took another 100 years to finish the story quantitatively, that is, to directly measure the numerical strength of the force of gravity, rather than its general properties, at which point, the story of gravity was effectively closed until Einstein's general relativity.

Outline

I. As you recall from the last lecture, gravity is universal, and circular motion results from a steady pull toward the center.

    A. When you are walking in a circle at a steady speed, two things are going on with each step: You're taking a sideways step (tangent to the circle) and an inward step (returning back toward the center of the circle). Each inward step represents a change in your velocity.

    B. Remember, acceleration tells us two things: in which direction the velocity is changing and how rapidly it is changing. When you think about uniform circular motion (just walking steadily around in a circle), you might not think that you are accelerating toward the center, but in fact, this acceleration can be measured in m/sec^2.

    C. What does this measurement depend on? A little geometry and careful thought can tell you the numerical amount of acceleration given just your sideways speed and the radius of the circle.

II. High-quality astronomical information was available to Newton, enabling him to quantitatively check the success of his theory of motion for planets.

    A. The distance to the Moon was known, even by the ancient Greeks.

        1. People also knew the duration of the Moon's orbit, about a month.

        2. Keep in mind that the circumference of the Moon's orbit is the distance traveled. If the distance traveled and time taken are known, then the average speed of the Moon's orbit could be calculated. Knowing the speed and the radius then allowed Newton to calculate the Moon's acceleration.

    B. We might expect the acceleration of the Moon to be the same as that of any object on the Earth, namely, 9.8 m/sec^2. Newton found, however, that the Moon's acceleration was roughly 3600 times smaller than this.

    C. Is the force of gravity the same that far away from the Earth?

        1. The Moon's distance from the Earth is roughly 60 times the Earth's radius (the Earth's radius is approximately 6000 km).

        2. If you're holding an apple in your hand on the surface of the Earth, you are a certain distance away from the center of the Earth. The Moon is 60 times farther away from the center, and its acceleration is 3600 times smaller.

        3. Newton saw, then, that gravity decreases as an object gets farther away from the Earth; specifically, the force of gravity decreases as the square of the distance.

        4. If the object is twice as far away from the Earth, gravity is 2 squared = $2 \times 2 = 4$ times weaker. If the object is 60 times farther away, gravity is $60 \times 60 = 3600$ times weaker.

III. Newton invoked a new principle, the universal law of gravity, to make sense of his observations.

    A. Gravity still affects all objects, but its strength weakens with distance.

    B. The force of gravity points from the center of one object, such as a planet, to the center of another. Recall that the force must be directed toward the center in order to maintain the circular motion.

C. The force of gravity also depends on the mass of the two objects involved. Indeed, it is directly proportional to the masses.

D. Given that the Earth and the Moon are so massive, the force of gravity between them must be huge, but does that mean that the acceleration is also huge? N-II ($F = ma$) tells us that the answer is no. The large force on the Moon is canceled out by its large mass (or inertia).

E. We can use this universal law to compute the force of gravity on the Earth.

    1. Again, the distance from an object on the surface of the Earth to the center is about 6000 km. Climbing a tree makes that distance about 6000.003 km, which wouldn't make much difference in your calculations of the force of gravity. Even at the top of Mt. Everest, the distance to the center of the Earth is only about 6010 km.

    2. You must get much farther away, to astronomical distances, to notice that the force of gravity is getting weaker. At 6000 km *above* the Earth's surface, the force of gravity would be 4 times weaker.

IV. Although it helps us understand a broad variety of complex phenomena, such as the motion of the planets, the tides, and so on, Newton's law of gravity is descriptive, not explanatory.

A. A child who says that a pen falls to the floor "because of gravity" is not explaining the effect but merely giving it a name. (We need Einstein to go to the next step.)

B. The new law involved a new kind of physics—a *force law* of action at a distance. Not everyone liked this (strange!) idea, including Newton.

C. A goal of physics is to make as few underlying basic assumptions as possible to explain as broad a spectrum of phenomena as possible.

V. There is one missing piece to the story we've talked about so far. Newton's law of gravity is still just one of proportionality.

A. As we've said, all objects on the Earth accelerate at 9.8 m/sec². The reason this acceleration is universal is that the force of gravity, on one side of the equation $F = ma$, depends on the mass, but there is also a mass on the other side of the equation; thus, the two masses cancel, leaving always the same numerical value for acceleration.

B. The Earth is accelerating toward the Sun, as is the Moon. As long as they are at the same distance from the Sun, all objects accelerate at the same rate.

    1. If we added another planet, much more massive than the Earth, according to Newton's laws, the force from the Sun would be proportional to the mass, but the acceleration would be inversely proportional to the mass; the two would cancel, and we wouldn't be able to tell the difference.

    2. Thus, the Earth doesn't have to be the mass that it is; it could have been any mass and its orbit would still be the same.

    3. In the Newtonian era, then, the mass of the Earth could not be known by looking at its orbital motion.

C. Newton's law of gravity *almost* helps us determine the mass of the Earth.

    1. The magnitude of the force of gravity is *proportional to* the mass of one object and the mass of the other object divided by the square of the distance between the two.

    2. The phrase *proportional to* points to one number, a *proportionality constant*, that must be found.

    3. Attempting to determine this universal constant of gravity became a significant intellectual and experimental task in Newton's time and afterward. The problem was ultimately solved by Henry Cavendish 100 years after Newton (in 1798) in an exquisitely difficult and delicate experiment.

    4. By combining his results with the lunar acceleration, Cavendish was able to "weigh" the Earth, giving important knowledge to geologists, astronomers, and other scientists.

D. In an absolute sense, gravity is a stunningly weak force, the weakest fundamental force we know of. Yet, because the Earth and Sun are so big, it has played a dominant role in the discovery of physical laws, not to mention in our lives.

E. In the next lecture, we'll look at Newton's third law and start to think about some issues beyond gravity, such as energy and momentum.

Essential Reading:

Thinkwell, "7: Gravity."

Hewitt, rest of chapter 8.

Hobson, rest of chapter 5.

March, rest of chapter 4.

Recommended Reading:

Crease, chapter 5.

Gonick, chapters 2–7 continue to span this material.

Questions to Consider:

1. What do Newton's apple and the Moon have in common?

2. How *could* you figure out the radius of the Earth using only observational data? The distance from the Earth to the Moon? The distance from the Earth to the Sun?

3. Newton's law of gravity says that the gravitational force between any two objects grows as they get closer as the inverse of their distance. If you are standing on the Earth, isn't your distance *zero*? (In which case, does his law of gravity predict an *infinite force*? Why not?)

4. If the Sun suddenly collapsed into a white dwarf star, with the same mass concentrated into a vastly smaller volume, what would happen to the Earth's orbit? (The answer may be a little surprising. What does Newton's law say matters for determining gravity and, therefore, orbit?) What would happen if the Sun somehow suddenly lost half its mass?

5. If you have two objects, each 1 kg, at a distance 1 meter apart, they will feel the spectacularly small gravitational force of 7×10^{-11} newtons. (That's 7 hundredths of a billionth of a newton.) Given that the force on a 1-kg object near the Earth's surface is 9.8 newtons (that's the weight of 1 kg) and knowing the Earth's radius (from our lecture), estimate the mass of the Earth. Given the radius, estimate the volume of the Earth. Now, you can compute the *density* of the Earth (mass/volume). How does this compare with the density of water? Of dirt?

6. How could you figure out the mass of the Moon?

Lecture Nine
Newton's Third Law

That Professor Goddard, with his "chair" in Clark College and the countenancing of the Smithsonian Institution, does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react— to say that would be absurd. Of course, he only seems to lack the knowledge ladled out daily in high schools.
—*New York Times* editorial, 1920

Scope: Newton's laws lead us to think about change in motion as arising from interactions between objects (which we call *forces*). Newton carefully articulated this in a third law of motion, commonly stated as: "For every action, there is an equal and opposite reaction." Newton's third law can be exasperatingly counterintuitive at first; you need to think carefully about your experiences and understanding of the first two laws to make sense of it. Re-expressing Newton's laws in terms of a new quantity, *momentum* (or "oomph," as I like to think of it) helps us to see the implications of Newton's laws more clearly and in a fresh light. Combined, Newton's second and third laws tell us that momentum is *conserved*—although it can shift around and reconfigure internally, the total (for isolated systems) never changes!

Outline

I. Newton's laws were a huge step forward because they showed us that motion can be understood from universal principles, not the character of individual objects.
   A. Forces between the objects are responsible for their behavior.
   B. Newton never wrote $F = ma$ in that form. He thought of forces as *interactions*.

II. Force as interaction led Newton to his third law, commonly stated as: "For every action, there is an equal and opposite reaction."
   A. Rather than focusing on only the one object that is being pushed, think of a pair of interacting objects, the "pusher and pushee."
      1. Imagine standing on an ice rink or on roller skates (which would eliminate friction) and pushing on a wall. As you push on the wall, it pushes back on you.
      2. You can think of this as a single interaction between you and the wall, or you can think separately of the force exerted on you by the wall and the force exerted on the wall by you.
      3. Thinking about the distinct yet intimate connection between these two forces led Newton to his third law, with implications from particle physics to rocket science to police accident investigations.
   B. If objects A and B interact (apply forces on one another), Newton's third law (N-III) says: "The force of A on B is always equal in magnitude (but opposite in direction) to the force of B on A." (You cannot touch without being touched.)
      1. We refer to these two forces as *force pairs*; forces always come in such pairs. Newton argued that it is productive to think carefully about the two separate forces acting on the two separate bodies.
      2. When you apply N-II ($F = ma$), you focus on *one* object. The F (force) refers to the force *on* that one object. The m (mass) refers to the mass of that one object, and the a (acceleration) refers to the rate of change of velocity of that one object. (If you wear roller skates and push forward on the wall, you go backwards.)
      3. N-III is a law of nature, a description of how the world works in the same vein as N-I or N-II. It is experimentally verified. Properly interpreted, there is no way around it.
   C. N-III allows us to understand more deeply such simple phenomena as how we are able to walk!
      1. Pay attention as you walk forward. You push backwards against the ground. (Notice the motion of dirt backwards as you move quickly from rest.)
      2. As you push backward on the ground, the ground pushes forward on you. This is N-III in action, or the evidence of a force pair: The harder you push back, the harder the ground pushes forward.
      3. As you walk, you are pushing the Earth backwards, but because of the huge mass of the Earth, its backward acceleration is so tiny as to be unmeasurable.

4. If there was no friction between you and the ground, you could not apply a backwards force to it, and in turn, there would be no forward force on you. (You cannot walk on a frictionless surface.)

III. N-III is subtle and has many consequences.

A. Consider a crash between a truck going 60 mph and a stationary compact car. The truck would plow right on through, mashing the car in the process. Is it really true that the force of the truck on the car is equal (in strength) to the force of the car on the truck? Let's look at the details of such a collision to keep our explanation concrete.

1. Picture a truck that weighs 11 times as much as the car. The collision is brief; the car is squashed and sticks to the nose of the truck. The *crash time*, the brief moment during which there is some interaction between the car and the truck, is the same for both vehicles. Immediately after the impact, the truck is still cruising down the highway, having slowed from 60 to 55 mph.

2. Our intuition says (correctly) that something far worse happens to the car than the truck. The car, after all, is squashed, and the truck is still moving down the highway. Is this a violation of N-III? No! Let's try to clarify what our intuition is telling us.

3. The truck slowed from 60 to 55 mph, a change of 5 mph. The car changed its speed from 0 to 55. Acceleration is "velocity change" / "time elapsed". The acceleration of the car is much greater than that of the truck. In the same time, the car's velocity change is 11 times greater! (55 mph more, compared to 5 mph less).

4. Thus, our intuition is correct; something is much different, much greater, for the car. That "something," however, is not the force but the acceleration!

5. If the car has 11 times smaller mass but 11 times greater acceleration, the product of $F = ma$ is exactly the same. This is what N-III tells us must always be the case. The amount of force of the car on the truck and the truck on the car is the same, but the consequences are different because the masses are different.

6. Think of $F = ma$ for just the driver in the car and the driver in the truck. They have similar masses but very different accelerations, and thus, they experience different forces.

7. Finally, note that the car speeds up, and the truck slows down. The forces (and, therefore, the accelerations) are opposite in directions. N-II and N-III dovetail.

B. In 1920, the *New York Times* ridiculed Robert Goddard (1882–1945), the father of modern American rocketry. He dreamed of rockets flying to the Moon or Mars, but the *Times* editor mocked his lack of understanding of N-III.

1. The editor thought that a rocket must have something solid (such as the Earth) to "push against" in order to move. This assumption is only partly correct.

2. Think of the rocket expelling small bits of fuel out the back. Even in the vacuum of space, the act of expelling a fuel molecule is an interaction. The rocket pushes on the fuel, and the fuel pushes back (equally!) on the rocket. This is the propulsive force that accelerates the rocket.

3. The *New York Times* apology came in print in the late 1960s when *Apollo 11* was on its way to the Moon, a little too late for Goddard.

C. N-III takes some getting used to, but when you make sense of it, it helps clarify what *force* means, how to visualize it and use it correctly. Coupling N-III with N-II led Newton to think about motion in a new and productive way.

IV. As we said, Newton never wrote $F = ma$ in his *Principia*. Instead, he was thinking about a quality of motion that we now call *momentum*.

A. Consider a small object (a point mass). It moves with velocity (v) and has mass (m). It has some inertia (resistance to motion) and something that we'll call "oomph."

1. Bigger masses carry more oomph. Imagine being hit in the stomach by a bowling ball versus a tennis ball. The bowling ball has more oomph.

2. Bigger velocity means more oomph, too. Imagine being hit by a pebble that someone has tossed at you gently versus a pebble fired at high speed from a slingshot.

B. Newton defines *momentum* (oomph) to be the product of mass and velocity; put another way, momentum = *mv*. This is a quantitative measure of oomph.

1. This formula is a definition, as opposed to $F = ma$, which is an experimentally verifiable relationship among different quantities.
2. The word *momentum* carries with it lots of English-language connotations. As always, we must be careful to distinguish our casual sense of the word from its new formal physics definition. In this case, however, the casual usage matches pretty well with what the new definition implies.
3. Momentum has a direction, the direction of velocity.
4. When you apply a force to an object, you change its momentum, and you change it at a particular rate.
5. Newton's way of thinking about his second law was not $F = ma$ but $F =$ change in momentum/time taken (momentum change per second). This rate of *change* in momentum is different from *momentum*; force is the rate at which momentum changes.
6. If you push an object that's at rest, you will change its momentum; it will start to move. $F = ma$ is one way to think about this phenomenon; $F =$ change in momentum/change in time is another way to think about it. These two ideas are the same.

V. N-II and N-III together tell us something essential about the world: For isolated systems, total momentum is conserved; it does not change (in total strength or direction) as time goes by.

   A. If $F = 0$, there is no rate of change of momentum. Something that does not change is *constant*, or *conserved*.

   B. Conservation laws are a big idea in physics. If you know how much momentum you start with and your system is isolated (that is, there is no outside force on it), total momentum will always stay the same.
      1. Having something (anything!) that stays constant in the face of arbitrary complexity is like an anchor, something solid we can count on and take enormous advantage of.
      2. No matter how complicated a system is (with arbitrarily complicated internal gears, pulleys, pushes, and pulls), if the overall external force is 0, then the total momentum (of all the parts added up) will never change. The momentum might redistribute itself, but the sum is a constant.
      3. Momentum and conservation of momentum are consequences of N-II and N-III and give us a powerful new way of thinking about interactions. We'll talk more about them in the next lecture.

Essential Reading:

Hewitt, chapter 5.

Hobson, end of chapter 4.

Thinkwell, "5: Momentum and Its Conservation."

Recommended Reading:

Gonick, chapter 8.

Questions to Consider:

1. When your coffee cup sits on the table, the table exerts an upward force on the cup. Why doesn't it accelerate upward? N-III says that there must be an equal and opposite force to the force of the table on the cup. What is that partner force? What does it act on?

2. Identify the equal and opposite force pairs in the following situations: You walk forward. A kayaker paddles. You get hit with a snowball. Your pen falls to the floor. Your pen strikes the floor after falling. (There might be more than one pair relevant in some examples, but for every force of "A on B," you need to come up with the equal and opposite force of "B on A.")

3. A donkey is attached to a cart. The donkey, who is pretty smart for a donkey (but doesn't yet fully grasp Newton's laws), says, "If I pull on the cart, the cart will pull *equally but opposite* on me. That's N-III. Given that those two forces are *equal and opposite*, the total force will add up to zero, and zero force means no acceleration. (That's N-II!) Apparently, then, no acceleration means that I'll never be able to budge the cart. It's at rest and will remain at rest. I think I'll just sit here and not even try." At which point, the donkey begins chewing on a carrot. How can you convince the donkey of its incorrect application of Newton's laws and get it to move? (No violence against animals, please. Use reason, logic, and physics only.)

4. What is an example of a system with no external forces?

5. If everyone in the United States jumped up at the same instant, what can you say about the total momentum of the "system" of planet Earth and all its occupants? Will the Earth "jerk" or not? (Would it be easily noticeable?)

Lecture Ten
Conservation of Momentum

The most incomprehensible thing about the world is that it is comprehensible.
—Albert Einstein

Scope: Introducing the concept of momentum shifts our perspective on Newton's laws. Without changing the underlying rules or adding anything fundamentally new, this moves our focus from force to interactions and from simple objects to systems. It allows us to broaden the scope of physics problems we can tackle. We can consider solid objects that can rotate, twist, even change shape, and we can examine questions of stability versus dynamism. The result is the Newtonian worldview—the universe as a deterministic clockwork, based on only a few basic underlying and unified principles.

Outline

I. If you think of N-II as $F = ma$, you tend to focus on one object and how it behaves. When you instead think of N-II and N-III in terms of momentum, you tend to "zoom out" to larger systems.

   A. Because forces always come in pairs, you can zoom out to find a larger system with no net external force on it.

   B. Momentum shifts how you think about force. Force causes a rate of change of momentum.

   1. Why does an air bag protect you? Your forward momentum will quickly change to zero in a crash. The air bag slightly increases the time for that change to take place—instead of the dashboard stopping you almost instantly, the bag "spreads out" the *time* over which you slow down.
   2. More time means a lower rate of change; if the momentum changes more slowly, the force is smaller. It's enough to save your life!

   C. Conservation of momentum does not mean that the momentum "here, of this thing" stays the same forever.

   1. Instead, the idea of conservation means that the total sum of momenta, added together, of all parts, is a constant as time goes by.
   2. Think of billiard balls knocking into each other; one stops, but the other starts. Momentum is conserved overall for the *system*, not for each ball separately.

   D. Consider a firecracker initially at rest on an ice rink. When it explodes, imagine two identical back-to-back pieces go flying apart.

   1. The system had no velocity to start, and because $mv = 0$, there is no momentum to start with.
   2. The exploding forces are all internal—no outside force acts on the firecracker; thus, momentum must be conserved.
   3. The two back-to-back pieces have equal and opposite momenta. The total momentum of this system is still 0.
   4. Momenta can cancel out just as easily as adding up, because they have a direction (equal forward and backward momenta add up to zero).

II. Conservation of momentum is helpful in situations that seem too complicated to fruitfully apply Newton's law directly, for example, with sudden or large internal forces.

   A. In the firecracker example above, the internal exploding forces are complicated and hard to quantify. Still, we can draw some clear conclusions.

   1. If a firework was launched and didn't explode, it would follow a simple parabolic arc as it fell to the ground.
   2. If the firework exploded into pieces, we know what that pattern looks like, and in fact, that recognizable pattern is a direct result of conservation of momentum.
   3. That's why firework displays look so uniformly distributed. No designer can predict *exactly* how the display will look, but they do know the general character of the result.
   4. Returning to our firecracker on the ice rink, suppose it explodes into two pieces, one more massive than the other. Momentum must be conserved, meaning that the momentum of the massive piece must be the same—equal and opposite—that of the less massive piece. But remember, momentum = mv.

Thus, to conserve momentum, the more massive piece will have a lower velocity than the less massive piece.

5. If you couldn't tell which piece was heavy and which was light, it might appear that momentum wasn't conserved (one piece moves away faster), but their oomph would be the same and in opposite directions—guaranteed!

6. When a little soccer player hits a bigger one, conservation of momentum can be very important—the little player goes flying!

B. Think of a car crashing into a stopped vehicle at an intersection. How do the police determine if the incoming car was speeding?

1. The crash involves complex internal forces that are hard to understand or characterize. Is it hopeless to try to analyze it?

2. There are two things going on in a crash of this kind: There's the crash itself and the resulting skid when the two cars (now stuck together) slide across the intersection. An external force, friction, ultimately slows the wreck to a halt.

3. By looking at the skid marks, the police can determine the velocity of the wreck (the hulk of the two cars stuck together) after the crash took place. Knowing this velocity and the mass of the wreck allows the police to use conservation of momentum to determine the speed of the incoming car as it hit the stopped car.

III. Conservation of momentum leads us to think about complex systems in a way that is ultimately as simple as point objects were.

A. The *center of mass* is the key to allowing us to think about complex systems in this way. The center of mass tells you *effectively* where the mass in an object is located.

1. For a symmetric object, that's literally at the center.

2. For a human body, the center of mass is determined by the weighted average of the locations of all the mass. In this case, the center of mass is somewhere behind your belly button.

3. If you reach forward, you move some of your mass in front of you, and your center of mass will shift forward. You can even shift your center of mass outside your body if you bend over into an arch.

4. If you follow the center of mass of your body, it obeys Newton's laws just as simply as a point would.

B. Consider a canoe in open water. Let's neglect the friction of water with the canoe. You are sitting at one end, and the momentum of the system starts at zero.

1. The center of mass of the system is not in the middle of the boat. It's shifted a bit toward the end where you are sitting because *you* have a lot of mass.

2. If you crawl toward the other end, you now have momentum. The canoe must move opposite you so that total momentum of the system is conserved (zero, the whole time!).

3. The canoe has moved, and so have you, but there was never any external force on the system. The system was at rest, and it remained at rest. Thus, the center of mass of the system never moved with respect to the world.

4. You moved in one direction and the canoe moved in the other direction, but the center of mass of you and the canoe as a system was always fixed.

5. To a physicist, you might say nothing happened in this system, despite its internal complexity.

C. The bottom line is that focusing on the center of mass of a real object simplifies the story enormously.

IV. Rotations around the center of mass are one last critical additional piece of the story for describing complex motion.

A. Recall the idea of superposition that we talked about with Galileo. If you think about a key ring flying through the air, it has both sideways motion and up-and-down motion. When you superpose these two motions, the result is a slightly more complicated motion, the arc. An Olympic high diver has the same motion. Now let's think about superposing yet another motion on that arc, which might be the high diver rotating around his or her center of mass.

B. Rotational motion is still just motion, and Newton's laws can be used to explain and predict all kinds of motion. We can always break complex motion down into various pieces.

C. Let's think of simple rotational motion, such as a bicycle wheel rotating around its axle. Focusing on just the spinning wheel, not the forward motion of the bicycle, we would see that the motion is not as complex as it originally seemed.

D. How fast is the wheel spinning? In other words, what would be the kinematics of this rotating object? It might, for example, move through 90 degrees of rotation every second and, thus, would take 4 seconds for a complete rotation. Note, however, that nothing is happening to the center of mass of the bicycle wheel.

E. In the same way, we could break down the motion of the high diver into rotations in three different spatial dimensions.

F. In analogy with momentum of an object moving along a straight line (*linear momentum*), we have *angular momentum* of a spinning object.

    1. A bike wheel on a rack, spinning but going nowhere, has no linear momentum but has plenty of angular momentum.

    2. Angular momentum is also conserved; in the absence of any outside "twists" (called *torques*), that bike wheel will keep on spinning.

G. Concentrating on the center of mass allows us to use Newton's laws to reduce complex systems back to point-like, simple objects.

V. We'll close by briefly mentioning one other piece in this story that moves from simplicity to complexity, which is *stability*.

A. When you're standing in place, how do you prevent yourself from tipping over? The answer can be found in $F = ma$. You must apply forces to your body in such a way that your center of mass doesn't accelerate in any direction. Of course, nature takes care of preventing up-and-down motion, and you use your muscles to keep yourself from tipping forward or backward.

B. When you build a building, you don't want it to acquire momentum when the wind blows. You want it to be stable.

C. When you build a porch, you don't want it to tip over (to acquire angular momentum!) when you stand at the edge. Again, you want it to be stable.

D. *Static equilibrium* is the buzzword here and has many practical applications. It's a direct application of Newton's laws: designing things so that the net force on (and torque or twist around) the center of mass will stay zero.

E. In future lectures, we'll begin to look at other combinations of mechanical quantities, similar to momentum (mv), that will allow us to explore ever-more complex systems but still work our way back down to Newton's laws.

Essential Reading:

Hewitt, chapter 7.

March, end of chapter 2.

Thinkwell, "7: Physics of Extended Objects" (particularly systems and center of mass, though you can go on to see as much as you're interested in).

Recommended Computer Sim:

Many Web sites have good collections of physics applets. For example:

1. www.walter-fendt.de/ph11e. Go to Lever Principle if you'd like to explore statics. (To add a mass, click on the sim and slide the mouse until the new mass "hooks.") What is the condition for balance? Do you have to have the same mass on both sides, or is there some other principle involved?

2. http://physics.bu.edu/~duffy/semester1. Scroll down to Center of Mass (in the left frame), and click on Motion with no external force. You will see a simulation of the person moving in the canoe discussed in this lecture. Look at the symbols at the bottom; there is a center of mass of the system but also a center of mass of the canoe alone and a center of mass of the person alone. Can you make sense of what's happening and relate it back to conservation of overall momentum? Explore more applets at this site; there are many nice ones!

Recommended Reading:

Gonick, chapters 10–11.

Questions to Consider:

1. Explain, using Newton's laws, how and why seatbelts help protect you in a crash.

2. When playing pool, the first shot is a single cue ball smacking into 15 target balls (all initially at rest, touching one another, in a triangular pattern). Imagine, for simplicity, that the pool table had no walls or ends (it's a very large table!). Describe the motion of the center of mass of the system (all 16 balls, target plus cue) before the cue ball reaches the target. After?

3. If two cars collide and one is initially at rest, is it possible for both to be at rest *immediately* after the collision? If so, explain how this might occur and how it is consistent with Newton's laws and conservation of momentum.

4. Is conservation of momentum still exactly true if there are internal frictional forces involved, or can internal friction "reduce" momentum of a system in some way?

5. How can you use a simple balloon to demonstrate the physics of rocket propulsion?

6. Angular momentum involves one extra thing we didn't discuss, the distribution of mass. If you shift mass close to the center (keeping the rotational speed constant), you have less angular momentum. Use this idea to explain how an ice skater can "speed up" a spin just by pulling his or her arms in. (It's a very dramatic and elegant demonstration/use of conservation of angular momentum!)

7. Two basketball players jump with the same upward velocity. Is there any possible way that one of them can have a longer "hang time" than the other? (Or is "long hang time" an optical illusion, based on watching some part of the body other than the center of mass?)

8. Stand with your heels against a wall and try to touch your toes without bending your knees or moving your feet. Only a small fraction of people can accomplish this task without falling over. What's the physics involved? (Where is your center of mass in relation to your feet?)

Lecture Eleven
Beyond Newton—Work and Energy

The whole of science is nothing more than a refinement of everyday thinking.
—Albert Einstein

Energy and persistence conquer all things.
—Benjamin Franklin

Scope: Isaac Newton thought of the world in terms of momentum and flow of momentum. A similar (but subtly different) perspective began to develop about 100 years after Newton and gained popularity as it became clear that it was enormously beneficial in making sense of real-life phenomena. This perspective involves thinking about energy and power, that is, the rate of flow of energy. Energy is a more abstract concept than force—you can't "touch" it in the same way—but our intuitions about energy will serve us well. This concept forms the basis of understanding practically everything, from chemistry and biology to geology and engineering. In this lecture, we introduce the ideas of work and energy to make sense of this new way of thinking about the world.

Outline

I. Energy is a central, critical idea in classical physics that moves us beyond strictly Newtonian ideas.
    A. The energy concept is used by scientists all the time. It's more robust and productive than the concept of forces. Biologists, chemists, and environmental engineers, not to mention politicians and homeowners paying their electric bills, care more about energy than force.
    B. Energy is a property of systems. Unlike force, energy can be quantified with a number. Energy can change form and move from one system or object to another.
    C. Thinking about the flow of energy is a powerful organizing tool for thinking about complex systems and interactions quite differently from force and motion.

II. It's a little tricky to define *energy* in a simple, global way. Like many physics words, it is not used in exactly the same way as it is in standard or casual English.
    A. We'll start with a closely related topic, *work*, which will lead us quite directly to the idea of energy. Work is yet another English word that we must define carefully.
    B. Work is a measure of what happens when a force *does* something, when it moves a body through a distance.
        1. Pushing a lawnmower (applying a force) requires work, as opposed to just leaning on a lawnmower which doesn't move.
        2. The harder you push, the more work you do. In addition, the *farther* it goes, the more work you do. Thus, we define *work* to be the product of force (how hard you push) and distance traveled. In other words, work equals force times distance.
        3. It's difficult to hold a stack of heavy books in your hand, but according to our definition, no work is being done; although you're applying a force, the books are not being *moved* through any distance.
        4. Technically, your muscles constantly twitch to hold up the books, so some "micro movement" is going on and, thus, some work. That's part of why the formal definition of *work* sometimes disagrees with our casual common sense.
    C. Work is measured in units of force times distance. In the metric system, a force of 1 newton moving something 1 meter is called 1 *joule* of work (named after James Joule, whom we'll talk about in future lectures). Lifting an apple gently up a few feet is about 1 joule's worth of work.

III. Energy is a number that characterizes a thing's capacity to do work. How much work you can do depends on how much energy you have.

A. When you do work, you are transferring energy mechanically. When you push a lawnmower, for example, energy is flowing from you to the mower (and, ultimately, into heating up the lawn).

B. Energy, too, is measured in joules. If you have 1 joule of energy, it means you could, in principle, do 1 joule's worth of work.

C. When a moving object, such as a swinging golf club, strikes a stationary object, such as a ball, a force is applied, and the struck object will move; in other words, work will be done.

1. Using Newton's laws, which tell us how force causes acceleration (which, in turn, changes velocity, which tells us how fast we're going and, therefore, how far we go in a given time...!), we can work out precisely how much energy a moving object has.

2. The faster an object is moving and the more massive it is, the more work it will be able to do in a collision, such as the one between the golf club and the ball.

3. The result is called *kinetic energy*, or *energy of motion*. This is the energy an object contains just by virtue of the fact that it's moving. Any moving object can, in principle, do work. All that matters is mass and velocity.

D. The formula for kinetic energy is $(\frac{1}{2})mv^2$.

1. This formula looks a bit like the one for momentum (mv), but the velocity enters twice. If the speed is doubled, more than twice the work can be performed. In fact, the result is four times the amount of work.

2. Note that there is no direction associated with energy.

3. A car going 55 mph has a certain amount of kinetic energy. Raising the speed to 75 does *not* double the speed, but it very nearly doubles the energy (try this on your calculator). When the U.S. government lowered speed limits from 75 to 55 many years ago, fatalities were dramatically reduced. A relatively small difference in speed makes a big difference in available energy!

4. Interestingly, the speed limit was lowered, not to save lives, but to save gas. Think about the logic of this situation in reverse: A car at rest has no kinetic energy. Pushing on the gas pedal transfers energy from the gas itself to energy of motion, that is, moving the car forward. To go from 0 to 55 mph requires a certain amount of energy: $(\frac{1}{2})mv^2$; to go from 0 to 75 mph requires almost double the energy.

IV. Kinetic energy is just one way that energy can be "stored."

A. *Potential energy* is the name for a different form of energy. Consider, again, a ring of keys tossed straight up in the air.

1. When you toss the key ring, you apply an upward force for a brief period. During that period, your hand is pushing the key ring and the key ring is responding. You did work on the key ring and, thus, you transferred kinetic energy to it.

2. As the key ring climbs, it slows down (because of gravity). At the top of its path, it's instantaneously at rest. Its kinetic energy is gone. Where did it go?

3. The energy has changed forms. Now, the energy is in the form of *gravitational potential energy*. The Earth–key ring system has stored up the original energy.

4. All the energy is still there, and we can get it all back just by letting the key ring fall back down again. When it reaches the starting point, it has the same ability to do work that it started with.

5. Again, the potential energy could be calculated, just as kinetic energy can be calculated. In this case, gravitational potential energy is directly proportional to mass and height (i.e., distance from the Earth).

B. There are many different kinds of energy.

1. Squeezing a spring stores *spring potential energy*. Children's toys often make use of this form of stored energy. As the toy sits on the floor, wound up, there is no motion. It doesn't have gravitational energy (it's on the floor), but it has spring potential energy, and when you let it go, it will do work (applying a force, moving something through a distance).

2. A can of gasoline has stored *chemical potential energy*. You might think of the chemical bonds as little coiled springs. Lots of energy is available in the gasoline, which can do work at a later time.

3. Hot water has stored *thermal energy*. The hotter the water is, the more energy it has. Here, the energy is hidden in the kinetic energy of the individual molecules.

V. Energy flows, but the total amount for any isolated system is conserved.

A. Energy can flow from body to body or from form to form.
   1. An example of body-to-body energy flow can be seen in the golf club striking the golf ball: The kinetic energy of the golf club converts to kinetic energy of the golf ball.
   2. The same example shows form-to-form energy flow: The kinetic energy of the golf ball is converted into gravitational potential energy as the ball rises into the air.
   3. The energy of the golf ball also turns into thermal energy when it smashes into the ground and stops (slightly heating both the ground and the ball).
   4. In all these processes, however, energy is conserved; the amount of energy that an isolated system starts with may transfer, but it doesn't change in overall amount.

B. The flow of energy characterizes all processes in the universe. It's another way of thinking about physics; rather than "pushes and pulls," we can think of work and energy transfer.
   1. For many reasons, biologists might prefer not to think about the forces on cells. Rather, they find it easier to think about the fuel for the cell that stores chemical energy, the amount and rate at which it transfers to other parts of the cell, and so on.
   2. The power station designer might prefer not to think about the pushes and pulls on gears at the plant (or electrons in your house). Rather, he or she might find it easier to think about the energy in the coal, the transfer into kinetic energy of spinning turbines, the flow of energy (in the form of electrical energy) to your home, the conversion into electromagnetic energy (light!) in your light bulbs, and so on.

C. What is so important about energy? In part, it's the fact that it's so simple (just a pure number) and that it is conserved.
   1. Remember that you can't get more energy out of a system than you put in. Don't waste your money on a perpetual motion ("free energy") scam that claims to give useful work without requiring an input of energy.
   2. Imagine trying to predict the speed of a roller-coaster car at some point along the track using Newton's laws. This would be a tedious and challenging math problem because you'd need to know the forces (and their directions) at every point along the way. In contrast, the principle of conservation of energy tells us the answer right away: The starting gravitational potential energy will be transferred to kinetic energy at the bottom of the hill.
   3. With Newton's laws, we think about individual objects and the forces on them. In thinking about energy, we step back and take a more holistic view.
   4. The flow of energy is a fresh perspective that allows very complex systems and problems to be analyzed and understood quickly and simply. We will come back to this concept many times in future lectures.

Essential Computer Sim:

Go to http://phet.colorado.edu, and play with Energy Skate Park. You can change the shape of the track or the strength of gravity. Use the Bar Chart option to try to keep track of the different forms of energy; then, you can go back to the Ramp. (There are buttons to let you view graphs of energy, as well as buttons to see bar charts of these.) Can you make sense of the results? Take your time, and try a few scenarios. It's probably best to turn off friction, at least at first.

Essential Reading:

Hewitt, start of chapter 6.

Hobson, start of chapter 6.

March, chapter 5.

Thinkwell, "4: Energy," particularly the introduction to "Work" and the introduction to "Conservation of Energy."

Recommended Reading:

Lightman, chapter 1.

Feynman Lectures, vol. 1, start of chapter 4.

Cropper, chapter 4.

Gonick, chapter 9.

Questions to Consider:

1. In what ways is the physicist's definition of *work* the same as, and different from, common English-language usage of that word? Give three different examples of *work* that you have done this week using the physics definition. How about the term *energy*? In what ways do we use this term in normal speech that differ from, or agree with, the physicist's definition?

2. A jelly donut has about 1 million joules of stored chemical energy in it. If you climb a mountain to "work off" that donut, how high do you have to go? (Gravitational potential energy is given by $m \times g \times h$, where m is your mass [in kg], g is the acceleration due to gravity [9.8 meters per second per second], and h is the height in meters.) What does this tell you about the "efficiency" your body has in terms of converting chemical energy?

3. Using the formula $(\frac{1}{2})mv^2$, estimate the kinetic energy of your car, driving at 60 miles/hr on the highway (that's about 100 km/hr, and 1 hr = 3600 sec). The total stored chemical energy in one gallon of gasoline is about 130 million joules. How much gas do you burn just to get the car up to speed? (Neglect friction and car efficiency. Then consider that typical car engines are about 20% efficient in ideal conditions.)

4. Trace the flow and conversion of energy (from form to form) involved when you throw a ball straight up in the air, from throw to catch. Where does the energy end up? How about when you push a lawnmower across the lawn? When you turn on the toaster in your house? (For this case, start right at the beginning, from nuclear fusion in the Sun that converts stored nuclear energy into electromagnetic energy in the form of sunlight.)

5. Does the Sun do "work" on the Earth as the Earth goes around in its orbit? (We have been a little crude in our definition of *work*. I said it was force × distance, but more carefully, it is only the part of the force *parallel* to the distance moved that counts.)

Lecture Twelve
Power and the Newtonian Synthesis

Physicists like to think that all you have to do is say,
"These are the conditions, now what happens next?"
—Richard Feynman

Scope: Thinking about physics in terms of energy and the flow of energy is a reformulation of Newtonian physics. It's not so much something new itself as a more novel perspective. The concept that energy can move from place to place and change forms helps us to understand how and why things behave as they do. The rate at which energy flows from one system to another (the *power*) tells us even more. These concepts then form the basis of understanding practically everything, from chemistry and biology to geology and engineering. We conclude this lecture by summarizing where we've been and where we're heading. Newtonian philosophy, that is, the experimental methodologies and the underlying realism, determinism, and ultimate simplicity, permeates classical physics questions. The world of classical physics is mechanical. The big ideas developed so far, particularly the ideas of force, matter, and energy; time and space; and conservation laws, allow us to tackle a broad scope of questions, which will be the subject of future lectures. Amazingly, none of these ideas has survived *completely* unscathed into modern physics, but they still form a *practical* foundation for our understanding of physics.

Outline

I. The rate at which energy flows is often important to think about. It can determine, for example, whether a cell in your body is functioning correctly or is sick. Physicists use the term *power* for the rate of energy flow: the amount of energy transferred divided by the time taken for the transfer.

A. It's easy to confuse power and energy, just as it's easy to confuse a thing and the rate of change of that thing. We've seen this distinction earlier with velocity and acceleration (acceleration equals the rate at which velocity is changing) and with momentum and force (force equals the rate at which momentum is changing). Power tells us how rapidly energy is flowing, not how much energy we have.

1. Think of a bucket of water with a hole in the bottom. Two quantities are involved in this system: the amount of water in the bucket and how fast it is pouring out.

2. At any given moment in time, knowing one of these quantities tells us nothing at all about the other. Over time, however, the rate of change has an effect on how much water is in the bucket.

B. Climbing up stairs requires a certain amount of energy. That is a fixed number, no matter how fast or how slow you go up the stairs. But the power demanded will depend on how fast you go, because power is energy divided by time taken.

1. The *energy* is determined by your mass and how high the stairs are. That's it—gravitational potential energy depends only on how high you lift something.

2. The *power* is energy used per second (or per minute or per hour). If you go up quickly, that is, in a short time, the power required will be high. If you go up slowly, the power requirement is smaller.

C. We measure power in units of joules per second. In the metric system, 1 joule/sec is called a *watt*, named after James Watt (1736–1819), inventor of the steam engine.

1. A 100-watt light bulb converts 100 joules of electric energy every second (into both light and heat energy).

2. You pay the electric company for energy used, not for power.

3. The new compact fluorescent light bulbs rated at 20 watts may be just as bright as a conventional 100-watt bulb because the old-style bulb puts out most of its energy in the form of heat.

4. A 20-watt bulb costs five times less each second that it's on than a 100-watt bulb. It converts five times less energy each second. If you leave the 20-watt bulb on for five hours but the 100-watt bulb for only one hour, the cost will be the same.

D. A car speeding up to highway speeds might convert around 100,000 joules of stored chemical energy (from the gasoline) into kinetic energy of motion of the car every second.

1. *Horsepower* is the English unit of power. A big car might be rated at 150 hp, which would be roughly 100,000 watts.
2. Gasoline has enormous chemical potential energy stored in it. One gallon of gas, if converted completely, can generate over 100 *million* joules.

II. Issues of energy (and the environment) can be complicated, but the bottom line often amounts to understanding energy and the rate at which energy is transferred.
   A. Conservation of energy means something different to a physicist and an environmentalist.
      1. For a physicist, the total amount of energy in the universe is conserved; it never changes. The same is true for any isolated system. That's the *conservation of energy* we've been discussing.
      2. For the environmentalist, conserving energy refers more to how efficiently energy is converted from one form to another.
   B. As mentioned earlier, energy is stored in different forms. Chemical potential energy of fossil fuels is *high-quality energy*, meaning that it can easily be converted into other useful forms of energy, such as energy of motion (to move cars or drive pistons). Electrical energy is even higher quality.
   C. The Earth is not an isolated system; we have a steady source of energy input from the Sun. It is relatively easy to convert this energy into thermal energy but more difficult to convert it into energy of motion.

III. At this halfway point in the lectures, let's summarize the big ideas we've covered so far; these include many of the basic "rules of the game," the underlying principles of classical physics.
   A. At the "micro" level, we set up Newtonian ideas about how to understand the behavior of physical objects.
      1. We started with kinematics, the description of motion. Knowing kinematics means that we can describe how things move in exquisite detail.
      2. Newton's laws provided the dynamics, that is, an explanation of the causes of motion. In particular, *F = ma* tells us the causes of motion. Why does the motion of something change? The answer: because a force is applied to it.
   B. At a slightly more macro level, we started thinking about momentum, a measurable property of objects and systems, defined in terms of observable (kinematic) quantities.
      1. Newton's laws can be reformulated in terms of momentum to tell us two key facts: If a system is isolated, total momentum is conserved. If it is not isolated, force results in a known rate of change of momentum.
      2. Momentum conservation is a powerful tool to simplify analysis and understanding of situations in which isolated systems experience significant, complex internal forces but no outside forces, such as collisions and explosions.
      3. Momentum conservation also allows us to simplify analysis in the sense of focusing on the center of mass, which continues to behave like a simple particle.
   C. At a still more macro level, the introduction of the concepts of work and energy lets us step even further back and think about the behavior and interactions of complex systems.
      1. Energy is a different measurable property of objects and systems, defined as the maximum amount of work which can be done. We also defined *work* in terms of force and distance.
      2. Energy is easier to work with than momentum because it's just a number; it has no direction.
   D. When we began this course, I said that we would be thinking about space and time, matter and energy, and force and motion. We now see that these are not isolated ideas; in physics, we combine these basic ideas in different ways.
   E. At this point, we can productively think about a huge spectrum of physical phenomena and describe, explain, understand, and predict them quantitatively. As the course goes on, we'll look at some other areas of physics, including electricity and magnetism, thermal properties of materials, light, and sound.
   F. On a more philosophical level, we've seen that classical physics has a mechanical worldview: The universe is like a giant clock, a huge, complicated mechanical system, operating with fundamentally simple and comprehensible rules.
      1. The classical worldview is deterministic: Knowing the "rules of the game" allows us to predict all physical behavior.

2. The classical outlook is also reductionist: There is a simple underlying story, and all the beauty and complexity of our seemingly magical world is understandable and derivable by considering smaller, simpler components.

G. We have focused so far on the basic principles of physics, and we still have many developments and details to consider. As we'll see, however, our knowledge of electricity, magnetism, light, and other topics will be built from this synthesis—this classical physics set of ideas—that we have examined so far.

Essential Reading:

Hewitt, end of chapter 6.

Hobson, end of chapter 6.

Thinkwell, "4: Energy" (especially "Conservation of Energy in General").

Recommended Reading:

Cropper, chapter 5.

Questions to Consider:

1. Look at your electric bill; figure out how much energy you used in the last month (in joules) and what your average power consumption was (in watts, which is joules/sec). How could you reduce these numbers? How could we, collectively, as a society, help? (What will happen if we don't?)

2. Two cross-country skiers climb the same mountain from two different sides. One side is very steep; the other is much less so. Both start at the same height and end at the top. If they take the same total time (they "tie"), which has done more work? Which required more power? What about if the one going up the steep side went faster and won? (Neglect human efficiency and work lost to friction for this scenario.)

3. You want to lift a washer/dryer up to a second-story apartment and can choose between hauling it straight up with a rope that runs over a good, low-friction pulley or pushing it up a ramp with good, low-friction rollers. Compare the total work done in both cases. Which requires more force? If you take the same time either way, which way requires more power?

4. Do you agree that the universe is fully deterministic? What does that say about human free will? Even if the laws of physics are fully deterministic, are there any practical limits to our predictive powers?

5. Do you agree that complex behavior of a system can always be understood in terms of the underlying parts and rules that govern the system? In other words, do you believe in reductionism? In all cases or just some? What are the limits of such a philosophy?

6. Does learning about the principles of classical physics make you want to learn more about it, or are you more interested in moving on to the more esoteric ideas of modern physics? (Or are you now ready to shift your focus to philosophy, history, religion, art...?)

7. In what ways did the shift to a classical scientific worldview (with its underlying realistic, deterministic, and reductionistic philosophical roots) influence non-scientific aspects of the world of the 1700s? Think in particular about the development of the American political system, shifts in religious power and influence, the world of art and music, and so on.

Timeline

1742 .... Anders Celsius, a Swedish astronomer, proposes a new scale for temperature based on the freezing and boiling points of water.

1750 .... After proposing that du Fay's "vitreous" and "resinous" fluids are not, in fact, separate, but really separate manifestations of the same fluid (a step in developing what we now understand as electric charge), Benjamin Franklin proposes his famous kite experiment, to prove that lightning storms are caused by electrical forces.

1757 .... James Watt creates his steam engine, offering a considerable increase in efficiency over previous models. It is the industrial drive to seek ever more powerful and efficient heat engines that pushes much of the study of thermodynamics through the 19th century.

1779–1783 .... Antoine Lavoisier isolates and identifies the element oxygen. He then uses this to debunk the phlogiston theory of combustion. Lavoisier goes on to propose the law of conservation of mass.

1785 .... Charles Coulomb proposes an inverse-squared law for electric force and proves his theory by careful use of torsion balance (basically a spring scale). The unit for charge is named in his honor. He also determines some of the relationships of forces between magnetic poles but categorically refuses to accept the idea that any connection between electric and magnetic forces could exist.

1788 .... Joseph Lagrange develops Lagrangian mechanics as the culmination of work over 16 years to simplify formulas and ease calculations. He is arguably the greatest mathematician of the 18th century, who made his claim to fame based on his work on wave propagation and analytical mechanics, both of which are extremely useful to physics.

1798 .... Henry Cavendish determines the mass of the Earth and, by doing so, calculates Newton's gravitational constant, g. (He did this through the use of a delicate apparatus developed by John Michell, who died and left the instrument to Cavendish.)

1800 .... Alessandro Volta invents the prototype battery (the *voltaic pile*). Prior to this development, all charge used for experimentation came from *Leyden jars*—capacitors that could provide a burst of electrical current. Volta's voltaic pile allowed the study of steady electrical currents.

1800 .... John Dalton becomes secretary of the Manchester Literary and Philosophical Society, through which he eventually publishes his atomic theory: All matter is made out of small, indivisible atoms.

1801 .... Thomas Young conducts his double-slit experiment. A beam of light is passed through two narrow slits, creating a diffraction pattern on a screen behind the slits. This is strong evidence for the wave nature of light.

1811 .... Amadeus Avogadro proposes Avogadro's law: that containers (at the same temperature and pressure) of different gases contain the same number of molecules, regardless of the chemical or physical properties of the gases.

1819 .... Hans Oersted discovers (possibly by accident, while preparing for a public lecture) that a wire carrying a current will divert a compass needle. This discovery provides the starting point for discovering the connections between electric and magnetic forces that would ultimately culminate in James Maxwell's work.

1820–1826 .... Andre Ampere develops the mathematical representation describing the Oersted discovery. This representation explains magnetism as resulting from the motion of many small charges.

1821–1831 .... Michael Faraday discovers the dynamo principle and demonstrates electromagnetic induction. Toward the end of this time, he begins to finalize the idea of a field—a concept whose mathematical expression would culminate in Maxwell's equations.

1824 ....Sadi Carnot formulates the idea of the *Carnot engine*, a steam engine of theoretically ideal efficiency. He uses this as a thought experiment to prove that temperature is the most important variable in an engine, not the material or specific construction details.

c. 1845 ....Henry Joule discovers and refines the principle that comes to be known as *Joule's law*— the conversion of mechanical work to thermal energy. In this year, Faraday also begins corresponding with William Thomson, who begins the initial efforts on mathematically expressing the ideas of Faraday's fields before passing the project along to Maxwell.

1847 ....Hermann von Helmholtz proposes the law of conservation of energy, the first law of thermodynamics, as a development of medical studies of muscles. He expands this, connecting heat, motion, magnetism, and electricity as various forms of energy.

1861–1868 ....James Clerk Maxwell unifies electricity and magnetism in a series of papers and proposes the electromagnetic nature of light.

c. 1881 ....Heinrich Hertz experimentally shows the existence of electromagnetic waves, providing the basis for radio technology, as well as proving Maxwell's equations.

1882 ....J. Willard Gibbs begins publishing his work on statistical mechanics.

1884 ....Ludwig Boltzmann develops a theory of blackbody radiation, deriving from statistical arguments the empirical relationship that had been discovered by Josef Stefan. He independently develops much of the same theories that Gibbs did.

1900 ....Max Planck publishes his theory of blackbody radiation. He builds strongly off of Bolztmann's statistical physics but introduces the requirement that the energy of photons must be contained in discrete bundles.

1905 ....Albert Einstein's "Miracle Year." He publishes three papers, any one of which would be enough to cement his place in science. All three in a single year make him a name for the ages and demarcate the end of the era of classical physics and the start of modern physics.

Glossary

AC (alternating current): Electrons in a circuit oscillate back and forth instead of flowing (compared with DC, or direct current).

acceleration: The rate of change in velocity; defined as change in velocity divided by time passed. Because velocity is a vector, so is acceleration (and we *can* have acceleration at constant speed if the *direction* of velocity changes!).

acoustics: The branch of physics that studies sound.

action at a distance: A property of many early theories (including Newton's theory of gravity or Coulomb's electric force law) stating that distant objects affect each other.

amp or ampere: The metric unit of current; it indicates the number of coulombs flowing past a given point each second.

angular momentum: A quantitative measure of how rapidly objects are turning coupled with how massive they are and how that mass is distributed. Angular momentum is a quality of any spinning object and is conserved (provided that the object is not subject to an external "twisting force," or torque).

angular speed: The rate at which something is spinning; can be measured in revolutions per second or radians per second. This is related to angular momentum but without regard to the mass or distribution of mass.

arrow of time: An abstract idea that dictates which processes are reversible, such as a billiard-ball collision, and which are irreversible, such as cracking an egg.

atom: Originally, the fundamental (indivisible) building block of all matter. Now, the smallest building block of chemistry, an individual particle of any element. Physically, a heavy nucleus with electrons orbiting.

atomic hypothesis: All physical matter is a composite of atoms.

battery: A mechanical device that turns chemical energy into electrical energy; if connected to a circuit, it will drive a current at a given voltage.

Brownian motion: The erratic motion of small but visible objects (e.g., dust) resulting from collisions with smaller (microscopic) atoms and molecules. Einstein's quantitative description of Brownian motion was the final piece of evidence in convincing physicists of the physical reality of atoms.

caloric theory: An early and now discredited theory of thermodynamics stating that heat is a physical fluid, rather than a transfer of energy.

center of mass: An average position of matter in an object; the effective point where gravity (or external force) acts.

charge: A property of all matter that determines electrical forces. Charge can be positive, negative, or neutral. Electric field lines start on positive charge and end on negative charge.

chemistry: The study of combinations of atoms and the resulting compositions and combinations of matter.

circuit: An electrically conducting path that can carry current in a loop.

classical physics: Basically physics before 1900; characterized as deterministic and realistic. Classical physics includes kinematics, mechanics, optics, thermodynamics, electricity and magnetism, and more (acoustics, fluid dynamics,...).

conduct: To allow charge to flow in a material. (A *resistor* still conducts, just with more resistance. The opposite of a conductor would be an insulator.)

conservation law: The situation that exists when some quantity remains unchanged during an interaction. For example, charge conservation states that the sum of all electric charges never changes in any particle reaction. Energy conservation states that although energy may transfer from particle to particle or form to form, the total (numerical) sum remains unchanged.

constructive interference: A defining property of waves in which two like waves add together, "building up." Note that if they are traveling waves, they then continue without affecting each other further on.

cosmology: The field of physics that studies the history, structure, and evolution of the universe.

coulomb: The unit of electric charge. One coulomb of charge is a *lot* of charge! (An electron carries 1.6×10^{-19} coulombs.)

Coulomb's law of static electricity: An equation that predicts the force between any two stationary charges at a given distance. Force is proportional to $Q_1Q_2/\text{distance}^2$.

current: The flow of electric charge (measured in amps).

DC (direct current): Electrons in a circuit flow in only one direction. (Compare with AC, or alternating current.) DC would result from a circuit with a battery; AC would result in household circuits.

degrees of freedom: A measure of the possibilities for the shape and location of an object. More degrees of freedom offer more possibilities to move and change. For example, a particle stuck on a rod can move only back and forth, restricting its degrees of freedom. In statistical mechanics , degrees of freedom of the pieces are very important in computing the entropy of a system.

destructive interference: A defining property of waves in which two like waves, out of phase, can cancel each other (add up positive and negative to give zero displacement) at one point.

determinism: A philosophical belief that if all physics and the exact state of the universe could be known at any given time, then the future could be perfectly predicted.

diffraction: The bending of light around corners.

dynamics: The branch of physics dealing with the "why" of motion. (Newton's laws are about dynamics of particles. Thermodynamics explains the flow of heat.) Compare with simple descriptions or, for example, kinematics.

E & M: The field of physics that studies the fundamental forces of electricity and magnetism, their sources, and their connections.

efficiency: Useful energy output divided by total energy input for a machine. (As we stated it in the course: "what you get" divided by "what you paid for.")

electric field (or e-field): A property of a location in space that indicates the force an electric charge would feel if placed at that location.

electricity: The forces and fields that result from the interactions of charged particles.

electromagnetic field: Maxwell's field that simultaneously describes electric fields and magnetic fields and their interactions. It is a unified, more universal way of thinking about electric and magnetic fields together. Light is an electromagnetic field—both electricity and magnetism are required to make sense of the phenomenon; they are intimately connected to each another.

electromagnetic wave (or EM radiation): The unique self-propagating wave of electric and magnetic fields. The only known wave that does *not* require any physical medium to propagate. At the right frequency range, this is commonly called *light*. At other frequencies, it includes (in increasing energy, which is also increasing frequency, but decreasing wavelength): radio waves, microwaves, infrared radiation, light, ultraviolet rays (UV rays), x-rays, and gamma rays.

ellipse: A particular kind of stretched circle; the path of planets in orbit. Mathematically, one of the *conic sections*.

energy: A measure of the amount of work (as defined by physics) that an object can do, at least in principle.

entropy: A quantitative measure of the disorder of a thermodynamic system.

equilibrium: A state of balance; a system or interaction of systems in which nothing macroscopic is changing.

experiment: A controlled test or procedure, often one that compares the predictions of a theory with the behavior of the universe.

experimentalist: A scientist who primarily devotes his or her time to creating and running experiments to better understand nature (as compared to a theorist). This is a more modern specialization/distinction; in the classical physics era, many scientists played the roles of both experimentalist and theorist.

field: The physical manifestation of a force of nature, present throughout space. An alternative way of thinking about forces, rather than "action at a distance."

field lines: A visualization tool to picture how electromagnetic fields appear in the presence of sources (charges or currents). A *field line* shows which way test charges would *start* to move if released at that point (tangent to, or "along," the field lines). Where the field lines bunch together, the forces are strongest.

force: A push or pull on an object; this is what causes acceleration. Force has a strength and a direction. Force is the quantitative measure of interactions of objects.

force field: The idea that a source of force produces something (a field) in all of space, whether or not there is an object there to feel it. For example, the Earth produces a *gravitational force field* around itself.

freefall: The idealized motion of an object falling due to gravity, without air resistance or any *other* forces. (A parachutist is in true freefall only briefly: Air resistance builds up quickly, ultimately becoming just as important as gravity, at which point the parachutist falls at constant speed.)

frequency: A measurement of how many times an object oscillates in a second; it is measured in hertz, or Hz. Thus, 60 Hz means "60 cycles each second."

frictionless: An approximation commonly made to simplify physics questions, in which we neglect the (often small but rarely truly zero) effects of air resistance or surface resistance to motion.

fundamental forces: The four basic forces that cause all motion and bind together all matter; they are the gravitational force, electromagnetic force, strong force, and weak force. (The latter two are not part of the classical physics story.)

gamma rays: High-energy EM radiation; see **electromagnetic wave**.

geocentric ("Earth centered"): The belief that the Sun and the entire universe rotated around the Earth.

gravity: One of the four fundamental forces. A purely attractive force generated between any two masses; it depends on the distance between the masses. Newton's formula of universal gravity is expressed as follows: Force is proportional to M_1M_2/distance^2.

ground: Electrical term referring to any object big enough to give or receive charge without itself becoming electrically charged; usually the Earth.

heat: A verb describing the transfer of thermal energy into or out of a system.

heliocentric ("Sun-centered"): The belief that the Earth, along with the rest of the solar system, revolves around the Sun.

hertz: The unit of frequency; it indicates number of cycles per second.

inertia: The tendency of an object in motion to remain in the same motion; also, a quantitative measure of the resistance of any object to change in its velocity (for a given force). Mass is the direct measure of inertia.

infrared radiation: See **electromagnetic wave**.

insulate: To prevent the flow of electrons through or on a material. Many materials (wood, plastic, and so on) are good insulators. Insulators can "break down"; for example, a high-voltage source can cause a spark, which means a conducting path has been created in what was previously an insulator.

interaction: A synonym for *force*; a way in which particles transform or perturb one another.

internal forces: Forces between objects *inside* a system. (Distinguished from *external forces*, which arise from something *outside* a system.)

invariant: Any property that remains unchanged over time.

kinematics: The study of physics in which motion is described. Kinematics of particles involves the relationships among position, velocity, and acceleration over time.

kinetic energy: The energy an object has based purely on its speed. The classical formula for kinetic energy is $(1/2)mv^2$.

law: A fundamental theory on which many other theories are based; a pattern or relationship that is extremely well established experimentally. However, even a "law of nature" may not be true in certain limits. For example, Newton's law of gravity must be modified in extreme situations, such as near a black hole. Newton's second law must be modified at velocities near the speed of light or for subatomic particles.

light: Visible electromagnetic radiation. See **electromagnetic wave**.

macroscopic: Anything of "human scale"; bigger than what can be seen with a low-powered microscope; very roughly larger than micrometers.

magnetic field (B field): A property of a location in space that indicates the force a moving electric charge (or a permanent magnet) would feel at that location.

magnetic poles: The magnetic analogy to charge; the points on a magnet where the field lines enter or exit the magnet. (There are north and south magnetic poles.)

magnetism: Another fundamental of force of nature; also, the study of magnets, currents, and the interactions among them.

mass: A measure of how much "stuff" an object has; the measure of inertia of a body; the quantity that determines the gravitational force on an object.

matter: A generic term for everything made of atoms (or the material components of the world). Matter has mass.

medium: The background material that supports a wave. For example, water is the *medium* for ocean waves; air is the *medium* for sound waves.

microscopic: Referring to a scale smaller than the human scale; invisible to the naked eye. Roughly, the molecular scale; certainly smaller than a fraction of a micrometer. Often synonymous with *atomic scale*.

model: A simplified way of thinking about or picturing the workings of a complex system. For example, a solid object can be modeled as a number of microscopic hard spheres, connected by a grid of simple springs. A model need not always be literally correct, but it allows scientists to make predictions and understand systems.

modern physics: Physics from 1900 until today, which primarily deals with the very small (quantum physics) and the very fast or very massive (relativity). Modern physics has branched out to include studies of particle physics, plasmas, cosmology, lasers, and much more.

molecule: A chemical building block that is not fundamental but is built up out of a bound state of two or more atoms; for example, an H_2O (water) molecule.

momentum: A measurable property of objects (or systems). Related to the tendency of an object to continue in its motion; the "oomph" an object would have if it hit you. (*Force* tells you the rate at which momentum changes.) Momentum is *defined* for a particle to be mass × velocity.

monopole: A beginning or end of field lines (e.g., a positive charge is always at the beginning of electric field lines). Important because no one has ever found a magnetic monopole; therefore, magnetic field lines can never begin or end—they must form loops

motion: The description of the change in position of an object over time, measured by velocity and acceleration. "At rest" is a state of motion in which the object has zero velocity and zero acceleration; its position is not changing.

neutral objects: Objects with equal positive and negative electric charge, thereby appearing to have no charge at all.

Newton's second law (N-II): The heart of dynamics; the law of nature that says that force causes any mass to accelerate according to the formula $F = ma$, or as Newton would write it, force = (change in momentum)/(time

taken). The formula is a *vector equation*, meaning that the *direction* of the force tells you the *direction* of the acceleration.

nucleus: A bound collection of protons and neutrons; the center of atoms.

Ockham's razor: A scientific principle basically stating that if all else is equal, then the simplest theory is more likely to be right.

optics: The study of light and how light travels through and between materials. (Geometric optics thinks of light as *rays*; physical optics tends to think of light as *waves*—both can be important!)

parabola: A mathematical shape that describes the path of a thrown object; commonly seen in archways. Mathematically, one of the *conic sections*.

particle: A discrete bit of matter; an idealization or simplification used to think about objects whose internal structure is irrelevant. (A *fundamental particle*, such as an electron, has mass but no relevant volume.)

particle physics: The study of the fundamental constituents of nature and their interactions with one another.

periodic table: Dmitri Mendeleev's organization of atoms into a simple table, in increasing order of weight, which shows the underlying structure of atoms.

physics: The science of the physical, measurable world. The study of matter and energy, space and time, and the structure and interactions of things in the world.

position: The place an object is located at a given time.

potential energy: Energy that is stored in an object to be released later (e.g., the chemical potential energy of gasoline); commonly refers to the gravitational potential energy an object has simply by virtue of being a height off the ground. Potential energy arises from interactions; for example, gravitational potential energy is a manifestation of the force of gravity and the work it can and will do if objects are allowed to fall toward one another.

pressure: Force per unit area.

quantum mechanics: The physical theory that tells how microscopic particles behave (as contrasted with classical or Newtonian mechanics, which is based entirely on force and Newton's laws).

radio waves: See **electromagnetic wave**.

reductionism: The philosophical principle that complex systems can be understood once we know what they are made of and how the constituents interact.

reference frame: The perspective from which a person makes measurements. An *inertial reference frame* is one in which Newton's first law holds.

relativity: A deep principle of physics that says that the laws of physics are the same in every inertial frame. Galileo postulated this, but the generic term is now usually reserved for Einstein's theories, which describe the motion of particles moving at high speeds. Special and general relativity modify our conventional views of space, time, and gravity (but do *not* say that "everything is relative").

resistor: An element in a circuit that reduces the current that can pass for a given voltage. The filament in a light bulb is a good example of a resistor.

rotational motion: See **angular speed**

special relativity: See **relativity.** Einstein's 1905 theory describing the motion of particles moving at high speeds. (*Special* means that the theory is limited to observers moving with steady velocity and ignores gravity.)

speed: A measure of the rate at which an object's position is changing per second; how quickly an object is moving. (Distinguished from *velocity*, speed is just a number; it has no direction associated with it.)

stability: A qualitative measure of how difficult it is to change the state or orientation of an object (e.g., a pencil standing on end is very unstable, while a pencil laying on its side is more stable).

static electricity: The study of electric effects arising from charges that are not moving.

static equilibrium: A state in which an object is subject to zero net force (and zero torque or "twisting") *and* does not feel a large or increasing force if it is moved. Thus, a balanced pencil is in equilibrium, but the equilibrium is not *static* because the slightest perturbation will remove the pencil from equilibrium.

superpose: Adding two forces or fields according to the rules of vector addition. Two opposing forces *superpose* to yield a total force of zero. Two parallel forces *superpose* to yield a doubly strong force.

system: Any group of objects under consideration.

temperature: A measure of the average thermal energy an object has. From a more practical perspective, temperature is what thermometers measure!

test particle: A theoretical particle of infinitely small mass and charge used to map out force fields (without itself changing the field).

theorist: A scientist who primarily devotes his or her time to studying the mathematics and concepts in current physics to extend the limits of those theories (as contrasted with an experimentalist).

theory: A well-tested, organized way of understanding a broad variety of physical circumstances. It is not an idle "guess" or speculation (as the term is sometimes used in standard English); physicists do not use this word to mean "I have a theory about what's going on here." Examples include Newton's theory of gravity or Einstein's theory of special relativity. These are mathematical and physical formulations that organize and consolidate vast amounts of data. Theory combines facts, laws, and tested hypotheses.

thermal energy: The total energy an object has stored internally, in the form of kinetic energy of vibrations of its atoms.

thermodynamics: The study of temperature, heat, and thermal energy.

UV or ultraviolet radiation: See **electromagnetic wave**.

unification: The goal of physicists to find a deep connection between forces. Electricity and magnetism were unified by Maxwell in the 1860s; they are both manifestations of one underlying *electromagnetic field*.

vector: A mathematical arrow that contains information about the direction and size of a quantity. Examples of vectors include velocity (which is not just speed but also direction) or force (which is not just how hard a push is but also which direction it is in). Contrast this term with a *scalar*, which is just a number, for example, temperature or mass.

velocity: The rate at which an object's position is changing per second; how fast and in what direction an object is moving. (*Speed* is the magnitude of the velocity.)

volt: The unit of electric potential in a circuit; a quantitative measure of the electrical potential energy per unit charge. Voltage differences tell, very crudely, the amount of "pressure" felt by electric charges in a circuit.

wave: A self-propagating disturbance (usually of some medium, except for EM waves) that can carry energy but is not itself a particle.

wavelength: In a wave, the distance between repeating parts of the wave.

work: The physics term for the result of a force pushing (or pulling) on an object over some distance. Work is form of energy transfer. The definition is: work = force $\times$ distance traveled, where one counts the component of force only in the direction of motion.

X-rays: High-energy electromagnetic radiation. Often used as a synonym for *gamma rays*, although X-rays connote slightly lower-energy radiation. See **electromagnetic wave**.

Great Ideas of Classical Physics
Part II
Professor Steven Pollock

Steven Pollock, Ph.D.

Associate Professor of Physics, University of Colorado, Boulder

Steven Pollock is associate professor of physics at the University of Colorado, Boulder. He did his undergraduate work at MIT, receiving a B.Sc. in physics in 1982. He holds a master's and a Ph.D. in physics from Stanford University, where he completed a thesis on "Electroweak Interactions in the Nuclear Domain" in 1987. He did postdoctoral research at NIKHEF (the National Institute for Nuclear and High Energy Physics) in Amsterdam from 1988–1990 and at the Institute for Nuclear Theory in Seattle from 1990–1992. He spent a year as senior researcher at NIKHEF in 1993 before moving to Boulder.

From 1993–2000, Professor Pollock's research work focused on the intersections of nuclear and particle physics, with special focus on parity violation, neutrino physics, and virtual strangeness content of ordinary matter. Around the time he received tenure at CU Boulder, Professor Pollock began shifting his attention to the newly developing discipline-based research field of physics education research. This field now represents his full-time physics research activities.

Professor Pollock was a teaching assistant and tutor for undergraduates throughout his years as both an undergraduate and graduate student. As a college professor, he has taught a wide variety of university courses at all levels, from introductory physics to advanced nuclear and particle physics, including quantum physics (both introductory and senior level) and mathematical physics, with intriguing recent forays into the physics of energy and the environment and the physics of sound and music.

Professor Pollock is the author of *Thinkwell's Physics I*, a CD-based introductory physics "next-generation" multimedia textbook. He became a Pew/Carnegie National Teaching Scholar in 2001 and is currently pursuing classroom research into replication and sustainability of reformed teaching techniques in (very) large lecture introductory courses. Professor Pollock received an Alfred P. Sloan Research Fellowship in 1994, the Boulder Faculty Assembly (CU campus-wide) Teaching Excellence Award in 1998, and the Marinus G. Smith Recognition Award in 2006. He has presented both nuclear physics research and his scholarship on teaching at numerous conferences, seminars, and colloquia. He is a member of the American Physical Society, the Forum on Education, and the American Association of Physics Teachers.

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Great Ideas of Classical Physics

Scope:

Physics is the science that tries to understand the deep principles underlying the world we live in. It's about understanding and describing nature. It's about *things*, as opposed to biological or even chemical *systems*. *How* do things move? *Why* do they move? How do they *work*? Physicists search for deep patterns, for the fundamental simplicity and unity of measurable phenomena. In this course, we will follow a theme-based, quasi-historical path, highlighting the central concepts, ideas, and discoveries of classical physics. *Classical* here refers to scientific work done up to the start of the 20th century, that is, essentially all physics before the quantum theory and relativity. It is the physics of everyday life, the physics of a deterministic "clockwork" universe, with enormous explanatory and predictive power! We will spend a little time getting to know the characters who played key roles, including Galileo, Newton, Faraday, Maxwell, and others, but the emphasis of the course is on sense-making: What have physicists learned about the world? What are the key underlying laws of nature? What are the primary organizing principles? How can we use these ideas and connect them to our personal experiences?

Physics is a broad field of study and can be approached from many angles. We begin with a venerable branch of physics known as *mechanics*, the study of forces, energy, and motion. The word *mechanics* might make one think of car engines, and in some ways, that's a good metaphor. Engines are complicated, but they are built out of simple and comprehensible parts, each of which serves a simple purpose. When put together, they create a familiar, useful, and understandable (by mechanics!) whole. But *mechanics* in physics is not about cars; it's the study of how just about anything moves and what makes objects behave as they do when acted on by forces. It's a study that will help us understand a vast and disparate array of phenomena, from Olympic high divers, to the display of sparks in a firework on the 4th of July, to the path of the Moon in the night sky, or the ceaseless bounce and jitter of atoms in a gas. We will focus on the central concepts: What do we know, and how do we know it? We'll ask where the ideas came from and how we might test them. And, of course, we'll ask what we can do with this knowledge. Classical mechanics is primarily the physics of Isaac Newton and a host of other brilliant characters who laid the groundwork for understanding the world that is still relevant 400 years after its beginnings. Our goal is to walk away with a sense of the order and coherence, the basic structure and principles of this foundation of physics.

Mechanics sits underneath the rest of physics a bit like the foundation of a great cathedral. The second half of the course will add the edifice, structure, and turrets. We will need to understand the ideas behind *electricity* and *magnetism*, forces that dominate our technological world and lead to understanding of the structure of all matter and light. This investigation leads naturally to *optics*, which was unified with electricity and magnetism in a brilliant stroke in the mid-1800s. In this context, we will briefly consider *waves* and the myriad phenomena that become understandable, and intimately related to one another, once we grasp the basic ideas and consequences of vibrations. We will need to learn separately about *heat* and *thermodynamics*, a branch of classical physics that deals with everything from understanding car engines and power supplies to making a perfect cake. This course of study takes us right up to the start of the 20th century.

One final comment: Mathematics plays a special role in science, one very dear to physicists, but we will not (and need not) focus on math in this course. Although skipping the equations limits, to some extent, the depth to which we can learn physics, the concepts themselves are, by and large, sensible, intuitive, and comprehensible through metaphor, life experience, ordinary logic, and common sense. From time to time, however, we may follow brief mathematical detours to appreciate the power and beauty of more formal or symbolic reasoning!

Notes on Course Materials: Suggested readings and computer simulations are listed with each lecture, using the abbreviations noted below.

Essential Computer Simulations ("Sims"):

These are all available at http://phet.colorado.edu and should run on PC or Mac. (Some of the Java applications require a fairly current Mac OS.)

Essential Reading:

Thinkwell   Professor Pollock's *Thinkwell Physics I*, www.thinkwell.com.

Hewitt   Paul G. Hewitt, *Conceptual Physics*, Addison Wesley, 2005.

| Hobson | Art Hobson, *Physics: Concepts and Connections*, Prentice Hall, 2006. |
| March | Robert March, *Physics for Poets*, McGraw-Hill, 2002. |

Recommended Reading:

Feynman	Feynman, Leighton, and Sands, *The Feynman Lectures on Physics*, Addison Wesley, 1963.
Cropper	William H. Cropper, *Great Physicists*, Oxford University Press, 2001.
Gleick	James Gleick, *Isaac Newton*, Vintage, 2003.
Lightman	Alan Lightman, *Great Ideas in Physics*, McGraw Hill, 2000.
Crease	Robert P. Crease, *The Prism and the Pendulum*, Random House, 2003.
Gonick	Larry Gonick and Art Huffman, *The Cartoon Guide to Physics*, Collins, 2005.

Lecture Thirteen
Further Developments—Static Electricity

Science is built up of facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house.
—Henri Poincare

Scope: For 200 years following the publication of the *Principia*, growing numbers of scientists followed the path laid out by Newton—a path paved from a philosophical, mathematical, theoretical, and experimental groundwork. The scope of "physics" expanded steadily and rapidly, and we can only touch on the many "great ideas" developed in this period: electricity, magnetism, waves, optics, and the grand unification of those ideas. Heat and temperature, chemistry, and the atomic worldview make up another path for us to follow. We will study some of these grand ideas in upcoming lectures—a few very briefly and some in more detail—to get a sense of the sweeping scale of accomplishments of classical physics. In this lecture, we begin our story of post-Newtonian classical physics with the "new" forces of static electricity and magnetism. We'll look at static electricity as a classic example of a systematic investigation into a force of nature, but we'll see that this "new" force still fits in tightly with the Newtonian framework.

Outline

I. Let's begin with a road map for the rest of the course.

A. In covering some new topics, we will always begin with Newton's ideas about forces, momentum, and energy and conservation laws.

B. In the second half of the course, we will talk about the fundamental constituents of the world, particularly atoms and their motion. We'll see that the motion of particles is connected to theories of electricity and magnetism, as well as theories of light and optics. We will also explore thermodynamics.

C. We will discover a new hero in this part of this course, James Clerk Maxwell (1831-1879), who is to electricity and magnetism what Newton was to the fundamental, underlying laws of mechanics. As we'll see, electricity and magnetism are evident everywhere in our world, especially in our technology but also in basic structures.

II. In Newton's day, electricity was a curiosity. People were aware of the phenomenon of static electricity but didn't begin to investigate it scientifically until about 100 years after Newton.

A. We're all familiar with static electricity. Think of walking across a carpet, touching the doorknob, and getting a shock or pulling apart clothes that have just come out of the dryer. Whenever anything sticks together, like the clothes, that implies a force of nature, and in this case, the force is not just friction.

B. Let's investigate static electricity using a simplified approach.
  1. Benjamin Franklin (1706–1790) helped start us on the path toward our current model of electric charges. In addition to flying the kite in the electrical storm, Franklin conducted experiments in which he rubbed various objects together, such as cat fur on amber or glass rods.
  2. Try a similar experiment on your own: Take about a foot of tape and fold over the ends to make tabs for pulling the tape up. Label this piece of tape *b* for "bottom." Place a second piece of tape on top of the first and label it *t* for "top"; then, stick both pieces of tape, now stuck together, down on a flat, clean table. Next, duplicate the experimental setup. Play around with the tape by ripping it off the table, then ripping the two pieces apart.
  3. It will be immediately obvious that the pieces of tape are charged. You'll also discover that different things happen to the top tape and the bottom tape. Two top tapes, for example, will repel each other, but a top and bottom will attract.

C. Let's construct a simple model to help us describe and understand the basic phenomenology of static electricity.
  1. Recall our discussion of what a model is: a simplified, descriptive picture. It must be consistent with known experiments and lead us to predictions about future experiments.

2. In the accepted model of electricity and magnetism, the world is made of atoms that carry electric charge. Electric charge is the quantity that exhibits the force of static electricity.

3. The tape experiment shows us that we need two types of charge to explain the results. Ben Franklin named these types of charges *positive* and *negative*.

4. How did Franklin know that there wasn't a third type of charge? Ockham's razor (named for a medieval philosopher, William of Ockham) suggests that we use the simplest explanation to understand complex phenomena. In other words, we don't add another charge because we aren't required to by the data.

D. Franklin's choice of *positive* and *negative* for the names of the two charges is helpful to our understanding of electricity, because it leads us to think of adding *plus* and *minus* charges. When we add positive and negative charges, the net charge is zero.

E. According to our model, the world is filled with positive and negative charges, and as we deduce from the tape experiment, opposite charges attract and like charges repel.

F. Newton saw that the gravitational force between two masses arises because of the mass. In the same way, the electrical force arises because of the charge. As we'll see in an upcoming lecture, we find the strength of the electrical force by multiplying the charges. Again, with multiplying, the positive and negative sign convention neatly summarizes the fact that opposite charges attract and like charges repel.

G. Our model is predictive and explanatory, but it doesn't tell us what charge is; it only postulates that charge exists.

1. With our model, you can see that combing your hair separates charges; the comb becomes negatively charged and your hair becomes positively charged. Your hair stands on end because all those like charges are repelling one another.

2. You can also understand why a balloon will stick to you after you rub it on your shirt, but why does it stick to the wall? The answer is that the wall also has electrical charges in it. Any negative charges in the wall that are free to move will be repelled by the balloon; any positive charges in the wall that are free to move will be attracted to the balloon. Separation of charges takes place again.

H. In one respect, Franklin's naming convention may be slightly confusing: We now use the term *electrons* for particles that carry negative charges, and these are the particles that move most easily in nature, although we might tend to associate positive charge with movement. Nonetheless, the simple story of static electricity has been spectacularly useful

III. Let's turn briefly to magnetism.

A. Find a child's set of magnets and experiment with them on your own. You'll find that magnetic force is quite similar to electric force. Instead of positive and negative charges, we say that magnets have *north* and *south poles*, which attract and repel each other analogously to charges.

B. One difference between magnets and static electricity is that magnetism seems to be permanent, whereas static electricity tends to fade with time for ordinary objects.

IV. We now have only a very basic understanding of static electricity. In future lectures, we'll see that the lightning bolt that Franklin was investigating; forces of nature, such as friction; and the high technology we now use all arise simply from the postulation of positive and negative charges and the electrical forces (ultimately, using Newton's law) between them.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Balloons and Static Electricity and John Travoltage. Do the balloons behave realistically? Are they conductors or insulators? How about the walls? Is charge flowing in the walls? Can you understand why the balloons stick to the wall, even though the total charge of the wall is zero? Why doesn't John Travoltage generate a spark immediately? Why does he have to build up some charge first? What role does the doorknob play? Why do you need it?

Essential Reading: Hewitt, start of ch 21, Hobson, ch 8.4, March, start of ch 6.

Recommended Reading: Gonick, chapter 12.

Questions to Consider:

1. Suppose somebody proposed to you that we are attracted to the Earth, not because of gravity, but because of static electrical forces. How could you convince this person that he or she is incorrect?

2. Try the tape experiment described in the lecture. What variations can you come up with? Can you determine which piece is positive and which is negative? Can you explain all your observations by hypothesizing only two charges (positive and negative), or do you need more?

3. Buy some toy magnets—not kitchen magnets but small bar magnets with two clear poles, like the plastic-coated, super-strong magnets that come with ball bearings as in a child's building kit. How are these magnets the same as and how are they different from the charged tapes? Can you prove that they are not attracting and repelling because of forces of static electricity? Can you build a compass out of these magnets?

4. Suppose that Ben Franklin had reversed his choice of which material to call *plus* and which to call *minus*. Would this change any of our laws of physics? What would be different?

Lecture Fourteen
Electricity, Magnetism, and Force Fields

Since Maxwell's time, physical reality has been thought of as represented by continuous fields, and not capable of any mechanical interpretation. This change in the conception of reality is the most profound and the most fruitful that physics has experienced since the time of Newton.
—Albert Einstein

Scope: In the last lecture, we introduced a "new" force in nature, electricity, and we constructed a model in which there were two kinds of electric charge, positive and negative. *Electric charge* is a term we used to describe the source of the static electrical force. Using our model, we saw that like charges repel each other and opposite charges attract. In this lecture, we'll move away from thinking of electric charge as "action at a distance," as Newton did, and begin thinking about electrical *fields*. This concept will help us to understand electricity better and to reformulate the way we think about gravity. The key player in the origination of the mathematical theory of static electricity was Charles Coulomb, a French scientist and engineer working in the 1780s. Coulomb's experiments with static electricity were similar to those conducted by Henry Cavendish to measure the force of gravity. We'll also look at the work of Michael Faraday, the British physicist who introduced the concept of a force field, and we'll see how this idea allows us to dispense with action at a distance and visualize force as a local phenomenon.

Outline

I. Charles Coulomb (1736−1806) discovered the fundamental mathematical relationship describing static electrical forces in the 1780s.

   A. To understand the gist of Coulomb's experiments, imagine charging up a balloon by rubbing it on your shirt. You'll discover that the charges on the balloon tend to stay put. The side of the balloon that you rubbed will be highly charged; the other side of the balloon will not be any more charged than it was to begin with. In physics, the balloon would be called an *insulator*, that is, an object in which charges can't migrate easily. Metals have the opposite property; in metals (*conductors*), charges spread out easily.

   B. Coulomb experimented with metal spheres, which allowed him to distribute charges and measure the forces between them.

   C. In honor of Coulomb's work, electric charge is measured in units called coulombs. One coulomb (1 C) is a significant amount of electric charge; a balloon rubbed on your shirt might have only 1/1,000,000 C

II. Let's look back again at the force of gravity.

   A. Masses cause a gravitational attraction, and the force of gravity is a constant of nature (measured by Cavendish) multiplied by the mass of one object times the mass of a second object, divided by the square of the distance between the two objects.

   B. Coulomb discovered that electricity could be described in much the same way, using the idea of charge rather than mass. Multiplying the charge on one object (measured in coulombs) by the charge on a second object will tell us how strong the force is between those two objects. Coulomb also discovered that static electrical attraction or repulsion, like the force of gravity, declines with greater distance between the two charged objects.

   C. There are some similarities between the force of electricity and the force of gravity, but the two forces are *not* the same thing. For instance, in considering the force of gravity, we know that all masses attract, but with electricity, both attraction and repulsion take place.

III. Like Newton's law, Coulomb's law was still a description of mysterious "action at a distance," which Newton himself was not comfortable with. The resolution to the problem of two unconnected objects somehow influencing each other was the idea of a *force field*, introduced by a British physicist, Michael Faraday (1791−1867).

   A. Faraday was originally a bookbinder. His lack of formal mathematical training compelled him to think of visual ways to describe and understand complex phenomena, such as electricity and magnetism.

B. Let's also use a simple picture to think about the idea of a force field: Imagine a mattress with a heavy bowling ball in the middle; the bowling ball is the *source* of a force.

    1. The mattress sags in the middle; that is, the mattress curves down and inward in all directions toward the bowling ball. The curved surface of the mattress offers some potentiality of force. We could verify this potentiality by placing a marble on the edge of the mattress and watching it roll toward the center.

    2. Next, we could place the marble at different points all around the mattress and draw arrows to represent the force created by the source (the bowling ball).

    3. If we remove the marble, what we have left are arrows drawn on the mattress, which represent a *force field*. Nothing is happening on the mattress, but the possibility is there, and if we placed the marble on the mattress again, something would happen. In other words, a force field exists, whether or not we test it.

C. We can extend this example to a gravitational field.

    1. Instead of a bowling ball on a mattress, think of the Sun in the middle of the solar system. If we let go of a test mass near the Earth, it would be pulled toward the Sun. We could again draw arrows in three-dimensional space, which would all point toward the Sun.

    2. Even if we remove all the planets from the solar system, the gravitational force field still exists, whether or not a test mass is available to show it.

D. The electrical field is a slightly more abstract way of characterizing electrical forces.

    1. A balloon rubbed on your shirt can serve as a source of an electrical field. In this case, we have to use a test charge, rather than a test mass, to see the effects of the electrical field. If both the balloon and the test charge are positive, we would draw an outward-pointing arrow to represent their repulsion.

    2. The force felt by the test charge depends on how strong the test charge itself is. This idea is akin to unit prices in grocery stores. A grocery store might have a unit price of $2.00 per pound for beans. This "price field" exists throughout the store, but doesn't tell you how much you will pay for beans at the checkout counter. The price you pay depends on the size of the bag of beans you choose. In the same way, the strength of the attraction or repulsion felt by the test charge depends on the magnitude of its charge.

E. Faraday simplified the picture of a force field by replacing the arrows with lines drawn away from the charges. For a point charge, this is called a *radial field* because all the lines resemble the radii of a circle.

    1. Such a picture gives us an intuitive idea of the physics of a field. For example, the strength of the field is represented in this picture by how closely spaced the lines are.

    2. If we had a positive charge at one point and a negative charge at another, the field line diagram would become more complicated.

F. We could also map out a magnetic field. In this case, the tester would have to be another magnet, perhaps a compass needle.

IV. The idea of fields is powerful because it gives us a fresh way of thinking about force that doesn't involve action at a distance. With the idea of fields, we can consider force as a local phenomenon, and we can predict the strength and direction of the force on any object at any point in the field.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Electric Field Hockey (EFH) and Charges and Fields. EFH will give you a sense of the force on a charge. Keep it simple at first; try to make sense of the connection between the field and the motion. Think back to earlier examples—the force determines the acceleration (not the velocity). Can you arrange charges to make the test charge (the one that can move) do what you want? Notice the Field button at the bottom. When you turn that on, does the result make sense to you? For Charges and Fields, show only the E field (don't bother with V, for voltage, just yet). Add some charges and move them around. What does the "intensity" of the red arrows indicate? (Does that match with what you see when you add an E field sensor? Why is the length of the sensor arrow different from the usual red arrows?)

Essential Reading:

Hewitt, rest of chapter 21.

Hobson, chapter 9.1.

March, middle of chapter 6.

Recommended Reading:

Cropper, chapter 11.

Gonick, chapters 13 and 17.

Questions to Consider:

1. How would you experimentally distinguish an electrical field from a gravitational field? From a magnetic field?

2. You and I both set out to map out an electrical field in the laboratory. I use a test charge of 1 microcoulomb, and you use a test charge of 2 microcoulombs. If we both independently "test" the same point in the room, will we agree *numerically* on the value of the electrical *force* on our test charges? (If not, how will the forces be related?) Will we agree *numerically* on the value of the electrical *field*?

3. An electron and a proton are placed in an identical electrical field. Compare the electric forces on each of them. Compare the resulting acceleration on each of them (direction and "how big," relatively). (Note: Electrons have negative electric charge and are very light. Protons have positive electric charge of the same magnitude as the electron but are very heavy.)

4. What would it mean to say, "An electrical field is real"? What (if anything) does "real" mean, when you're thinking like a physicist? Can you ever see a field? Feel it directly?

Lecture Fifteen
Electrical Currents and Voltage

...after Faraday was made a fellow of the Royal Society[,] the prime minister of the day asked what good this invention could be, and Faraday answered:
"Why, Prime Minister, someday you can tax it."
—Frequently referenced but probably apocryphal quote

Scope: In the last lecture, we saw that an electric charge, acting as a source, creates a field in space, to which other charges respond. In this lecture, we'll look at the progress made in the 19th century in applying this understanding, which resulted in batteries, devices for storing charge, and simple circuit elements. Today, our lives are surrounded by electrical (and electronic) devices. The critical distinction (and connections) between voltage and current allows us to make intuitive sense of much contemporary electrical technology and phenomena.

Outline

I. Nineteenth-century progress in the understanding and applications of electricity was rapid and deep. As a direct result, electrical devices have become a significant part of our contemporary lives.

    A. The language of simple electrical devices requires understanding the concepts of *circuits*, *current*, and *voltage*.

    B. Our goal in this lecture is to build a mental model to answer questions about electricity, such as: What is electricity? How do we guide and control it? How can we understand manifestations of electricity, such as light coming from a light bulb, in terms of our underlying picture?

II. Let's begin with a couple of familiar terms: *insulator* and *conductor*.

    A. Electric charges constitute a property of material objects; in other words, material objects have charge on them. As mentioned in the last lecture, in some materials, such as a balloon, that charge tends to stay in one place, and in other materials, such as metals, the charge is allowed to flow. If the charge flows, the material is a *conductor*; if the charge is "stuck," the material is an *insulator*.

    B. Air is an example of a material that acts largely as an insulator. If we build up electric charges on a piece of tape, they will tend not to drift through the air. However, if we build up enough static charge in one spot, the electrical force between the charges can eventually push some charges into the air.

        1. With enough energy, an electric charge in the air can rip atoms apart. The atoms will later recombine (because the opposite charges attract each other) and release energy.

        2. That release of energy can take a number of forms, including a spark of light. This is the phenomenon we see in lightning bolts and in the spark produced when you walk across the carpet and touch another person or a metal doorknob.

    C. Another term we need in discussing electricity is *ground*, which we can use in both the standard English sense and a technical physics sense. The ground is a place for charges to spread out and neutralize.

III. How can we harness the flow of electrical charges for practical applications?

    A. We need a mechanism to both build up charge and provide a conducting path back to the ground. The result is an electrical circuit.

    B. In 1800, Alessandro Volta (1745−1827) discovered a simple setup of materials that served as an electrical "pump"—the first battery. The materials inside batteries separate charges and drive them to one end or the other. The minus sign on a battery means that negatively charged electrons are driven to that end. The plus sign means that positively charged ions are being driven to the opposite end of the battery.

    C. To use the battery, you need a connection, such as a wire, between the negative and positive ends; you can then sustain a flow of charges.

IV. Consider another metaphor to think about electrical circuits and the idea of voltage.

A. Imagine a device that lifts up bowling balls, similar to the return mechanism in a bowling alley. Our device lifts bowling balls up in energy. The term *voltage* is roughly a reference to energy in electrical circuits, that is, how high we're lifting the bowling balls.

B. The height to which we lift the bowling balls (to the tabletop versus to the attic) tells us how much work they're going to be able to do when we let them fall back down again.

C. If we pump up an electric charge, we've added energy to that electric charge, just as we've added energy to the bowling balls by lifting them to the attic. *Voltage* is defined as energy per charge, or energy per coulomb. Specifically, 1 volt refers to 1 joule of energy per coulomb.

D. A car battery is 12 volts. This means that 12 joules of energy is required for every coulomb of charge moved from one pole of the battery to the other. Every coulomb that flows through the wire connecting the positive pole to the negative pole yields 12 joules of energy.

V. In addition to voltage, we need to understand the concept of *current*.

A. With our bowling-ball machine, we need to know how many bowling balls we lift and let fall down every second. If we lift and let fall 10 balls per second, we will get a lot more work from the device than if we lift and let fall only 1 ball per second.

B. *Current* refers to the flow rate: how many charges flowing per second.

C. Instead of bowling balls, we can think of a water pump, moving water up into a reservoir. The height of the reservoir (the voltage) is significant. If we can pump the water up to a higher level, we will store more energy per gallon. The other important aspect of this system is how many gallons are flowing per second (the current).

D. The measure used for current is *amps*, named after André Ampère, whom we'll meet in a later lecture. One ampere of current flow is 1 coulomb flowing every second.

E. With real water pumps, the amount of water that will flow each second depends on the pipes that are used. A large pipe allows lots of water to flow through; a skinny pipe introduces more friction—*resistance*—and doesn't allow as much water to flow. The same is true of electricity: A thick wire allows relatively easy flow of electricity.

    1. The term *resistor* is used (unfortunately) for materials that are both highly resistive and not so resistive.

    2. We can think of resistance as adding friction to a circuit. As current flows through resistors, they dissipate energy and heat up.

VI. When we use electricity, we often need some kind of a pump. We've talked about using a battery as a pump, but the wall socket is also a kind of pump.

A. The two main prongs of a plug are rather like the poles of a battery; they, too, have a plus side and a minus side (which alternate in time).

B. When you plug in an appliance, the electricity flows through the two prongs, forming a complete circuit.

VII. What is dangerous about electricity?

A. High voltage by itself is not intrinsically dangerous. It's like having bowling balls in the attic; if the floor is strong enough (like a battery with a good insulator), preventing the flow of the bowling balls, there's really no danger at all.

B. If a bird lands on a high-voltage power line, it's in no danger. The danger would come if the bird were to stretch its wings and connect the power line with the ground. That opens up a conducting path for the charges to flow through the bird.

C. Multiplying voltage (energy per charge) by current (charge per second) yields energy per second, or power. High voltage, then, is potentially dangerous because it can yield a high rate of energy per second.

VIII. Every electrical device in your house is designed around these basic ideas, and again, we can trace this discussion back to Newton and his concepts of force—pushing and pulling charges—and energy.

Essential Computer Sim:

Go to http://phet.colorado.edu, build circuits with the Circuit Construction Kit, and play with Charges and Fields again (this time, turning on the voltage indicator). Where is the voltage high, and where is it low? The Circuit

Construction Kit (CCK) is my favorite sim. You can spend a lot of time with it, getting a sense of, and the connections among, voltage, current, and power. Try to answer question 1 below with the CCK! There are many more sims to play around with, which I leave up to you to investigate, including: Battery Voltage, Resistance in a Wire, Ohm's Law, Battery-Resistor Circuit, and Signal Circuit.

Essential Reading:

Hewitt, rest of chapter 21 and chapter 22.

Recommended Reading:

Gonick, chapters 15–16.

Questions to Consider:

1. Dig up a small bulb (e.g. from a flashlight), a battery, and a single piece of electrical wire. Can you make the bulb light? Once you have done so, try to find at least four different arrangements that light the bulb. How are they similar? What is the requirement for the bulb to light? What can you conclude about how the bulb is "wired up" inside, where you can't see it?

2. It's easy to confuse *voltage* and *current*. What is wrong with a news broadcaster saying, "20,000 volts of electricity flowed through the victim's body"? What language would you use to describe this tragic accident more accurately? In the end, what harms an electrocution victim, the voltage or the current (or something else)?

3. You have two glowing light bulbs. One is rated 100 watts (which means 100 joules/sec), and the other is rated 20 watts. What is the same, and what is different, about these two bulbs and the electrical flow through them? (Is the power the same or different? Current? Voltage?) What can you say about how much "resistance" each one offers? (This is tricky! A clue is that wall sockets in the U.S. are 120 Volts, no matter what you plug into them.)

4. When you get the bill from your power company, what do you pay for, electric power or electrical energy? How are these related? Look at your electric bill. Odds are that it tells you how many kWh, or kilowatt hours, you are paying for (1 kilowatt means 1000 watts, which is 1000 joules each second). Note that kWh is *not* kilowatts *per* hour! It is kilowatts *times* hours. If you can make sense of why your power company charges you for kWh, you'll have mastered the big ideas of power and energy from this lecture!

Lecture Sixteen
The Origin of Electric and Magnet Fields

Aye, I suppose I could stay up that late.
—James Clerk Maxwell, on being told on his arrival at Cambridge University that there would be a compulsory 6:00 a.m. church service

Scope: Despite all our wonderful technologies, electricity and magnetism are forces we only rarely experience *directly* (e.g., static cling or kitchen magnets). These two forces are distinct but intimately connected. We can create (electro)magnets out of completely nonmagnetic materials, making use of pure electric currents. And we can produce electrical currents by spinning magnets near wires. In this lecture, we zoom in on the *sources* of electric and magnetic fields and their myriad connections, leading to a deeper understanding of the unity of electromagnetic physics.

Outline

I. Let's begin this lecture by talking about magnets; specifically, we'll look at the commonalities and differences between electricity and magnetism.

   A. Magnets have two poles, north and south. As with electric charges, like magnetic poles repel each other and opposite magnetic poles attract.

   B. This phenomenon looks like action at a distance, but if you hold two magnets close together, you can almost feel the force field operating between them. A compass needle, which is a small magnet, responds to the magnetic field, just as a test charge responds to electrical fields.

   C. You can map out a magnetic field by placing a piece of paper over a magnet and sprinkling iron filings on the paper. The filings will arrange themselves in a field line pattern, showing magnetic fields looping from north to south poles.

II. What are the differences between electricity and magnetism?

   A. You can charge materials up electrically by rubbing them, but the same thing doesn't work for magnets. Most materials are not magnetic.

   B. Magnets stay magnetic for a long time.

   C. Compass needles do not deflect in the presence of electric charge. In other words, magnets are neither attracted to nor repelled by electric charge. This alone tells us that electricity and magnetism are two distinct forces of nature.

   D. By the same token, electric charges are not attracted to magnets. The Earth is a giant magnet, which causes all compass needles to point north. But there is no attraction of electric charges to magnets.

   E. Electric charges can be separated, but magnetic poles can not.

      1. I could charge up a balloon, hand it to you, and you could walk away with it; you would then have an isolated electric charge.

      2. If you cut a magnet in half, however, you would not end up with an isolated north pole or an isolated south pole; you would have two smaller magnets, *each* with a north pole and a south pole.

      3. If you *could* isolate a magnetic pole, scientists would call that a *magnetic monopole*.

   F. The bottom line is that electric charges interact with other electric charges, magnets interact with other magnets, and masses interact with other masses. Thus, all three forces at work here—electrical, magnetic, and gravitational—seem at first to be independent and unrelated.

III. In the early 1800s, Hans Oersted (1777−1851) discovered, while preparing for a classroom lecture, that electrical currents can produce magnetic fields.

   A. This discovery was a surprise. Electric and magnetic fields were assumed to be separate and distinct; Oersted found that flowing electric charges in a simple circuit create a magnetic field. Oersted's simple, reproducible experiment generated significant interest.

B. Merely closing a switch to allow current to flow creates a magnetic field, and can lead to practical applications.

IV. The French mathematician André Ampère (1775−1836) began to formulate a law to explain magnetic fields.

A. As we said earlier, static electric charges (that is, charges that are not moving) create electrical fields. The field lines in our earlier picture emanate in straight lines from (or toward) electric charges in the center.

B. With magnetism, you might think that the pattern of field lines created by an electric current would be similar; that is, you might expect to see radial magnetic field lines pointing away from a current-carrying wire. However, magnetic field lines run in circles around the electric current.

C. In thinking about this phenomenon, keep in mind that electric charge is flowing, but the field is static. Ampère worked out the mathematics to predict the magnetic field generated from any current in any strength.

D. You could run an experiment at home to create a magnetic field, although you would have to exercise some caution. You would also have to take into account the fact that the Earth has its own magnetic field; you would be superposing your magnetic field on the one that already exists on the Earth. What would be the result of this superposition?

1. Recall Galileo's superposition principle applied to forces: Two forces acting in opposition will cancel each other out; two forces acting in the same direction will add up.

2. If the magnetic field you create is aligned with the Earth's magnetic field, the resulting magnetic field will be stronger. If the magnetic field you create points in the opposite direction of the Earth's magnetic field (and is equally strong), the result is no magnetic field at all.

V. One very strange aspect of electricity and magnetism is that static electric charges don't generate magnetic fields, but moving electric charges do.

A. If I charge up a balloon and place it in a room, no magnetic field is generated. But now you enter the room in a slightly different reference frame, moving steadily through the room on a cart. From *your* reference frame, you are at rest, and the room is sliding by you at 2 meters per second. To you, the balloon is moving, which means that electric current is flowing, and a magnetic field is created.

B. Electric and magnetic fields are very real and intimately connected, but the value and nature of the fields are dependent on the observer. Ultimately, physicists will give the name *electromagnetism* to this one force of nature, which seems to have two sides to it.

VI. Let's return now to applications.

A. A certain amount of current will create a certain magnetic field strength. Doubling the current will also double the field strength. You can make a very powerful magnet simply by running current through coils of wire.

B. When you insert a key in your car, you complete a circuit that starts electricity flowing through a coil of wire (the solenoid). The resulting magnetic field is strong enough to pull an iron rod, engaging the starter.

VII. Where does the magnetic field of an ordinary kitchen magnet arise from? No obvious current is flowing to generate a magnetic field.

A. In fact, there is current in this situation, but it's microscopic. The full story requires modern quantum physics, but we can make basic sense of it with a simplified classical physics picture.

B. An atom of any material has a positive, heavy nucleus and negative electrons in orbit around it. The moving electric charge of the electrons constitutes a current. This current creates a tiny magnetic field; thus, atoms themselves are tiny magnets.

C. If nearby atoms are randomly oriented, the magnetic fields they produce will cancel. That's why ordinary materials aren't magnetic. But in special materials—such as iron crystals—the magnetic fields of the atoms align; adding these microscopic fields up creates a macroscopic magnetic field.

VIII. Faraday discovered moving magnets generate electrical fields, perhaps the most practically important discovery in the history of physics. Rotating magnets at a power plant are the source of the electrical field that pushes electrons through your toaster oven or computer.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Faraday's Electromagnetic Lab. There are tabs for different experiments. Look at the magnetic field; do you understand this representation of the field? The Pickup Coil variation lets you directly study Faraday's law of induced currents. In Electromagnet mode, turn up the voltage and see if you can visualize the circles of magnetic field around the coils.

Essential Reading:

Hewitt, chapters 23–24.

Recommended Reading:

Cropper, chapter 12.

Gonick, chapters 18–19 and 21–22.

Questions to Consider:

1. Opposite magnetic poles attract (north attracts south). A compass needle is a tiny magnet, and (by convention) we label the pole that points toward geographic north (Canada) the "north" end. (Seems reasonable; magnetic north points you geographically north!) Now think carefully (draw a picture) and decide which magnetic pole of the giant magnet that is planet Earth is the one located in northern Canada. (The answer may surprise you.)

2. Can a constant (steady, unchanging) magnetic field set into motion an electron initially at rest? Try to explain your reasoning carefully.

3. Particle physicists send high-energy microscopic particles through *bubble chambers*, where they leave a trail of bubbles as they pass, enabling physicists to track their motion. There is always a strong magnetic field in the bubble chamber, and some particle tracks form spirals, while others are straight lines. What can you conclude is different about these particles?

4. Iron is a magnetic material, but it is not always a "magnet." Most pieces of iron have no poles, but a magnet sticks to it. (Your refrigerator has iron in it that is not itself magnetized, but a magnet will attract to it.) Let's say I hand you two heavy, identical chunks of iron, one of which is magnetized, and the other is not. Think of at least three different ways you might figure out which one is the natural magnet and which is unmagnetized iron.

Lecture Seventeen

Unification I—Maxwell's Equations

From a long view of the history of mankind— seen from, say, ten thousand years from now, there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade.
— R. P. Feynman, *Lectures on Physics*, Vol. II

Scope: In the last lecture, we saw that electricity and magnetism are different forces of nature, but they seem to be connected in certain ways. For example, a moving magnet produces an electrical field and vice versa—a moving electric charge produces a magnetic field. In this lecture and the next, we'll refine our understanding of these forces and their connection. The unification of electricity and magnetism is one of the grand intellectual achievements of classical physics. The person credited with this synthesis is James Clerk Maxwell, a Scottish physicist working in the mid-1800s, who organized the work of Ampère, Coulomb, Faraday, and others into four simple equations that constitute the "rules" of electricity and magnetism. In the end, Maxwell was able to summarize everything we know about electromagnetism in a set of four relations, two for static situations and two for time-varying situations. Together with Newton's laws, these relationships quantify all electric and magnetic phenomena. In this lecture, we'll bypass the mathematics of Maxwell's equations and try to understand the underlying essence of each one.

Outline

I. The first of Maxwell's equations is similar to Coulomb's law; it describes electrical fields arising from electric charges.

  A. Maxwell combined Coulomb's work with that of a German mathematician named Carl Friedrich Gauss (1777−1855). *Gauss's law* involves looking at the outside of a region with an electrical field to deduce the nature of the sources inside. Think of encasing an electric charge in a bubble and observing the electrical field lines emanating from that source. If field lines are pointing outward in all directions, we can conclude that there must be a charge inside the bubble.

  B. Gauss's law is intuitive: Electric charge is the source of electrical fields, which emanate from the source. The same is true in reverse: If we see electrical fields pointing outward in all directions, we know that they must be emanating from a source.

  C. Gauss's law is both quantitative and qualitative: It tells us how strong the electrical field is and what pattern it produces. Gauss's law is also more robust than Coulomb's law. It accounts for multiple electric charges and for moving charges.

  D. Gauss's law is universal, requiring a fundamental constant of nature (measured by Coulomb). This constant is necessary to determine how strong the electrical field is for a given amount of charge.

  E. A dog sniffing around a barbeque grill can conclude that the smell of cooking food is emanating from the grill as a source. Gauss's law can be thought of in the same way.

II. The second of Maxwell's four equations is sometimes called *Gauss's law for magnetism*.

  A. This is a sort of negative law. If we encase a magnetic field in a bubble, we will *never* see field lines emanating from a source in the middle. In other words, there are no point-like sources of pure magnetic field lines in the universe—no magnetic monopoles.

  B. Even though this law is negative, it tells us something about the pattern for all magnetic fields in the universe: They never emanate from a point; they run in circles, never stopping or starting at points in space.

  C. Physicists have sought to falsify Gauss's law for magnetism (by finding a magnetic monopole) for 150 years, without success.

III. The third of Maxwell's four equations is also called *Ampère's law*.

A. As mentioned in the last lecture, Ampère's law tells us that a current (flowing electric charges) generates a magnetic field. Ampère's law is a rigorous description of this phenomenon, a mathematical formula that can be used to calculate the strength and direction of the magnetic field, just as Gauss's law can be used to determine the strength and direction of the electrical field.

B. Again, Ampère's law requires a numerical constant of nature to characterize the connection between the amount of electric current flowing and the strength of the magnetic field.

IV. The fourth of Maxwell's equations arose from Faraday's work and is usually called *Faraday's law*.

A. As we mentioned in the last lecture, Faraday realized that a moving magnetic field generates an electrical field; in turn, electric charges will respond to this field.

B. Faraday's law is the most directly practical and widely used of all the equations described so far. Sometimes called the *law of electrical induction*, it accounts for how we produce electricity in our homes and how we convert electrical voltages (via transformers) for such devices as laptop computers and cell-phone chargers.

V. In looking at these equations, Maxwell noticed an aesthetic "hole," a lack of symmetry.

A. According to Ampère's law, flowing electric charges create magnetic fields. At the same time, according to Faraday's law, changing magnetic fields produce electrical fields. If that's true, why wouldn't changing electrical fields produce magnetic fields?

B. To resolve this problem, Maxwell took a leap and hypothesized an additional term in Ampère's law, designed to make it symmetrical with Faraday's law. In making this leap, Maxwell drew on the rich tapestry of data from existing experimental and theoretical physics and realized that his hypothesis would have to stand up to the tests of mathematical and physical consistency, consequences, and falsifiability.

C. It took many years for Maxwell's addition to Ampère's law to be directly tested through experiment, but once it was, numerous practical applications were realized.

D. We now have two ways to produce a magnetic field, but why don't we have two ways to produce an electrical field? The answer: There are no flowing magnetic charges—no magnetic monopoles—in the universe.

VI. Maxwell's four equations enable us to understand the patterns of electrical and magnetic fields in any circumstances. Let's summarize them.

A. Static charges generate static electrical fields that show a radial field pattern, but there is no analogous source for magnetic fields because there are no magnetic monopoles.

B. Moving electric charges generate circular magnetic fields; further, a moving electrical field also produces a magnetic field.

C. Finally, a moving magnetic field produces an electrical field.

VII. Maxwell's equations focus on fields, leading us to think of nature, as we do today, in terms of field theory.

A. These equations are enormously practical. They tell us how to design devices ranging from a cell-phone antenna to a toaster oven.

B. Further, all of Maxwell's equations tie in with Newton's laws and help us see fields as "real." The equations fit beautifully with the classical physics worldview, enabling local, deterministic, and quantitative predictions and explanations.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Faraday's Electromagnetic Lab (check out the Transformer and Generator tabs if you haven't already). Then look at Radio Waves and Electromagnetic Fields. Can you understand the various representations of an electrical field? Which of Maxwell's equations are involved?

Essential Reading:

Hewitt, review chapters 21–24 (it's all there).

Hobson, start of chapter 9.

Recommended Reading:

Cropper, chapter 12.

Gonick, start of chapter 23.

Questions to Consider:

1. If magnetic monopoles existed in nature, what changes would we have to make to Maxwell's equations? Which equations would be modified? Would there be a new constant of nature to measure?

2. I have argued that Faraday's law (which states that any change in the magnetic field through a coil will generate electric currents) has had enormous technological impact, specifically with regard to electrical generation and transformers. What other pieces of everyday technology make use of Faraday's law? (Think of devices in your home, in your car, at the airport…) The list is quite long; can you come up with a half-dozen?

3. We have said that electric currents generate magnetic fields. Is there a measurable magnetic field near, say, the cord leading to a lamp in your house? (If not, why not?) We have said that *changing* the electrical field over time also generates magnetic fields. Since the current in the lamp cord is AC (alternating current, flowing back and forth), would *that* generate a measurable magnetic field? Why or why not?

4. Static charges feel a force only from electrical fields. Moving charges feel forces from magnetic fields, as well. This fact forms the basis for electric motors: You use electrical fields (e.g., from a battery) to run current through a metal loop situated in a static magnetic field. The current (moving charges) feels a force from the magnetic field and is pushed—it turns. That's all there is to any electric motor. What happens if you take the exact same device but disconnect the battery? What happens if, with the battery disconnected, you physically rotate the metal loop in the presence of this magnetic field? What important device have you just created?

Lecture Eighteen
Unification II—Electromagnetism and Light

And God said:

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot B = 0$$

$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

and there was light.
—Maxwell's Equations on a t-shirt popular at MIT when I was an undergraduate

Scope: Maxwell's equations synthesize and describe every aspect of classical electromagnetism, from lightning bolts, to electric circuits, to kitchen magnets. But Maxwell made another observation that went far beyond his original equations: He discovered they predicted a "new" phenomenon, an electromagnetic traveling wave, ultimately recognized to be light. All of optics, the remaining great branch of physics, was suddenly completely and deeply unified with electric and magnetic phenomena. Maxwell had provided a grand synthesis of all known fundamental forces of that era (*besides* gravity), allowing us to make sense of the spectrum of radiation and an enormous span of physics, as well as setting a compelling tone for ongoing physics research.

Outline

I. The most common motion in the universe is oscillation. The Earth, an atom, and a pendulum all oscillate. Maxwell asked: How would an electric charge behave if it were moving in this most common way?

  A. A static electric charge (an electron) generates an electrical field with straight lines pointing, in this case, in toward the charge. You might think of these lines as similar to the gravitational field lines pointing in toward a star.

  B. As the charge moves back and forth, the electrical field lines must move also in order to constantly point toward the charge.

  C. A moving electrical field, according to Maxwell's "extra term," will produce a magnetic field; the resulting magnetic field will oscillate.

  D. According to Faraday's law, a changing magnetic field will produce an electrical field.

  E. The original source in this system was a charge, which created an electrical field, which in turn, created a magnetic field, which in turn, created an electrical field, and so on.
    1. We can visualize this phenomenon by thinking of a pebble dropped into a pond. The pebble (the original charge) starts a disturbance (a wave) in the water that is self-propagating.
    2. In Maxwell's case, there is no water or other medium. The ripples from the original charge are fields in otherwise empty space.

II. These fields exist, but we have to think about them mathematically.

  A. We can find evidence for the existence of electrical and magnetic fields. Can we find similar evidence for the self-propagating phenomenon that Maxwell discovered?

  B. We already know that we can detect the oscillation of an electrical field by looking for a similar oscillating response in a test charge.

  C. Maxwell found that he could calculate the speed of propagation of an electromagnetic wave. The wave travels at a speed that is dependent on the two constants of nature from Maxwell's original equations. In

fact, the answer turns out to be 300 million meters, or 186,000 miles, per second—precisely the speed of light!

D. This result implies that the electromagnetic disturbance we've been talking about is light; light is nothing more than a traveling electromagnetic wave.

III. Maxwell's discovery unified electricity, magnetism, and light.

A. Think about a light bulb. When the filament gets hot, the electrons inside begin to move, producing an electromagnetic wave that travels outward. The electrons in your retina respond to this wave as it passes, because an electrical field always moves charges around. The moving charges in your retina, in turn, send electrical signals to your brain. As we know, our brains respond only to a certain narrow range of frequencies of these oscillations in the retina, and we "see the light."

B. At this point, we understand the nature of light and optics and that the electromagnetic wave of Maxwell's equations is not exotic at all.

IV. Maxwell published his work over several years around 1860, but it took 20 years for the scientific community to accept this revolutionary synthesis.

A. Experimental verification came with the work of a young German physicist, Heinrich Hertz (1857−1894). Hertz built an electric circuit called an *oscillator*, designed to allow current to flow back and forth. He then built another oscillator, similar to the first one but with no power supply. According to Maxwell, the electromagnetic wave from the first oscillator should spread across the room at the speed of light and cause the second oscillator to respond—and indeed it did.

B. In effect, Hertz had built a radio. On one side of the room was an antenna broadcasting a signal, and on the other side of the room was an antenna receiving the signal.

C. Again, picture a moving electric charge at one point in space, which creates a ripple of electrical and magnetic fields that causes other charges, at another point in space, to move.

V. Maxwell's work opened up a new branch of physics—physical optics—that allowed scientists to think about optics in a new way.

A. Instead of exploring the path of light rays through a prism or how a telescope might focus light, scientists could now think about the interaction of light (electromagnetic waves) with matter.

B. Light had been studied since well before Newton; in fact, Newton's career as a physicist began with his experiments into the nature of color. He believed that light was "corpuscular," that is, made of particles, but the technology was not available to either prove or disprove this theory.

C. In 1800, Thomas Young (1773−1829), conducted an experiment that convincingly proved that light is a wave phenomenon. For 60 years after Young, physicists wondered: If light is a wave, what material thing is "waving"? As we've said, Maxwell answered this question: Light is electrical and magnetic fields oscillating in empty space.

VI. Anything we want to know about light should, in principle, arise from Maxwell's equations, including its origin, propagation, and interactions with matter. We should be able to understand lenses, rainbows, prisms, diffraction, and many other phenomena.

A. Maxwell's equations tell us that light carries energy. A moving electric charge is experiencing a force and, thus, accelerates over some distance; as we know, force multiplied by distance equals work, and work is a transfer of energy. Where does the energy go in this case? It spreads out in the electromagnetic wave.

B. The speed at which this wave propagates, 186,000 miles per second, is independent of any details of the motion.

1. Red light and blue light don't differ in their fundamental properties, but blue light has a higher oscillation frequency.

2. An even higher oscillation frequency than that associated with blue light won't be perceived by the human brain; this is *ultraviolet radiation*. Still higher oscillation frequencies result in other kinds of electromagnetic radiation, such as X-rays or gamma rays.

3. A slower oscillation frequency than that associated with red light results in *infrared radiation*. This is another form of light, and we can build night-vision cameras that detect this form of radiation.

4. In honor of Heinrich Hertz, we measure frequencies in units of cycles per second, now called *hertz*. The wall plug in your house is 60 Hz; your eye responds to about 1 million billion Hz.
5. Beyond the infrared frequency is microwave radiation, and at a lower frequency still are radio waves.

C. Maxwell left a legacy of the unification of electricity, magnetism, and light, and an explosion of new ideas and applications that took off from his four equations.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Radio Waves and Electromagnetic Fields; Microwaves and Blackbody Spectrum are both worth exploring, too.

Essential Reading:

Hewitt, chapter 25.

Hobson, chapter 9.

Recommended Reading:

Gonick, end of chapter 23 and chapter 24.

Questions to Consider:

1. Why is Maxwell's change (addition) to Ampère's law needed in order to result in electromagnetic waves?
2. Is sound an electromagnetic wave? Why or why not? What are the similarities? What are the differences?
3. Suppose you had goggles that allowed you to see infrared radiation in much the same way you currently see visible light. What would the room you are in "look like"? In particular, what would be bright and what would be dim?
4. When astronomers see a distant supernova from another galaxy, they see a sudden increase in brightness of all colors of the spectrum (as well as radio signal, X-ray signal, and any other part of the electromagnetic spectrum they might be able to measure), all at the same time. How is this evidence that the speed of light is independent of frequency?
5. The Sun emits most of its energy in the form of electromagnetic waves, and most of that energy is found only in the near visible spectrum (from red to violet), with a peak in energy flow around yellow. There is relatively little energy emitted in the infrared range (or beyond) or the ultraviolet range (or beyond). Our eyes, of course, are sensitive to just this same narrow band of frequencies that the Sun emits. Is this a remarkable coincidence, or can you think of a reason for it?

Lecture Nineteen

Vibrations and Waves

The wireless telegraph is not difficult to understand. The ordinary telegraph is like a very long cat. You pull the tail in New York, and it meows in Los Angeles. The wireless is the same, only without the cat.
—Albert Einstein

Scope: In this lecture, we step back from the story of electromagnetism to think about a very different kind of physics—the description and understanding of objects that vibrate and the associated phenomenon of waves. Vibrations and waves are *everywhere* in the natural world, and they provide a wonderful counterpoint to our usual language and model of particles. Understanding the big ideas of waves, especially the remarkable feature of *interference* and the point-counterpoint of waves versus particles, plays a key role in the developing story of physics.

Outline

I. Vibrations and waves are everywhere in the physical world and provide a counterpoint to our usual language and model of particles.

A. Waves are a collective phenomenon, a way of seeing a simple pattern in complex situations. They have been studied since before Newton and were well known by Maxwell's time.

B. The "canonical" wave would be a pebble thrown into a pond, resulting in ripples of water spreading out. How can we *describe* this?

1. The water itself is the medium for the wave. The water molecules are being displaced from their equilibrium point; as the wave passes, they move up and down. In other words, the ripples that we see on the pond arise from the displacement of particles from their normal equilibrium level.

2. A wave is not a "thing" itself; it is a self-propagating disturbance. A classical wave has no obvious physical essence—no mass or clear position.

3. If you look at the ocean, you see waves spread out parallel to the beach, one after another. This motion is not localized at all; the entire ocean carries gigantic, spread-out traveling waves.

II. A subtle phenomenon takes place in the motion of a wave.

A. Picture a wave traveling from left to right. The water—the medium of the wave—is moving *only* up and down; it is not traveling sideways.

B. Water waves near the beach, where we most often see them, become nonlinear—the water splashes sideways—and the waves are no longer ideal classical waves. If you were sitting in a dinghy beyond the break, however, you would see that the waves cause you to bob up and down on the water; they do not cause you to start surfing.

C. Think of a field of wheat, disturbed by a rustling at one end. The wave spreads out and travels across the field, but no wheat stalk ever leaves its original spot. The wave travels across the field, but wheat does not!

D. Consider the "wave" in a stadium, when people rise up and down in their seats in a sort of contagious motion. The wave rushes around the stadium, but the people (the medium) ultimately stay in their seats.

III. Waves may seem to behave in some respects like particles, but the two are not the same.

A. Particles have mass and position and exist independent of any other material objects. None of these is a characteristic of waves.

B. Let's think about a Slinky® to visualize some of the differences between waves and particles.

1. A Slinky stretched out motionless on the floor is the medium.

2. Imagining holding one end of the Slinky fixed and jerking the other end up and down one time. A sideways pulse will travel from one end of the Slinky to the other.

3. The pulse almost seems like a material object; it obviously travels from one end of the Slinky to the other and will even recoil and travel back. With this behavior, it's easy to think that the pulse is somehow like a particle.

C. Waves are characterized by a frequency (measured in Hz), a wavelength (the distance from one peak of a wave to the next), and a velocity (the speed of the wave itself, not the medium).

    1. The speed of the wave arises from interactions of the medium. Generally speaking, the more tightly coupled the "pieces" of the medium are, the faster the wave will ripple.

    2. If you jerk one end of a Slinky quickly (rapid frequency), the pulse will have a different shape (wavelength), but the pulse's progress as a traveling wave will not be affected. (See the Essential Computer Sim at the end of this lecture.)

    3. If you stand up and sit down quickly in the stadium, you will affect how wide the stadium wave appears, but the traveling speed of the wave has to do with the interaction of you and the person in the seat next to you, not with your behavior alone.

    4. Maxwell saw this clearly with electromagnetic waves, which always travel at the speed of light.

IV. Waves are closely related to *simple harmonic motion* (*SHM*)—oscillations.

  A. The mathematics of SHM is described by the *sine wave*, which represents something moving back and forth smoothly, forever.

  B. SHM is ideal oscillatory motion. Do real objects in the world behave in this ideal way? To a large degree, the answer is yes. Electromagnetic waves are truly ideal; the Slinky and water waves away from the beach are fairly close approximations of SHM.

  C. What makes such motion, and why is it so common?

    1. Any material object that has a "home," an equilibrium point, is pulled back to that point whenever it is displaced. The result is generally SHM.

    2. Think of a guitar string that you pull away from equilibrium, creating tension in the string. As the string is pulled backed toward its original position, the principle of inertia takes over (an object in motion remains in motion), and the string moves past its equilibrium point. Then, of course, it's pulled back toward its original position again and so on.

    3. SHM takes place throughout the universe, for example, in the Earth orbiting the Sun (viewed from the side) or atoms moving in a crystal.

  D. How do we know when a wave is happening?

    1. If we zoom in on a wave, we see the SHM of the medium.

    2. If we zoom out, we see a wave traveling at some speed, and we no longer pay attention to the medium. We don't see the SHM; in fact, any point on the crest of the wave seems to move in a straight line, like a particle.

V. A defining characteristic of a wave is what happens when two waves come together.

  A. Picture the Slinky again, with a person holding each end. If each person creates a pulse and two waves begin to travel along the Slinky from opposite directions, what happens when they meet?

  B. If the waves were particles, they might break or bounce off each other, but in fact, the waves pass right through each other.

  C. The most interesting phenomenon takes place at the point of intersection of the two waves; this is called *superposition* or *interference*.

    1. If I send a 1cm tall "up pulse" along a Slinky and you send an "up pulse" from the other direction that is also 1 cm tall, at the point where they meet, we momentarily have a pulse that is 2 cm tall.

    2. If I send an "up pulse" and you send a "down pulse" from opposite ends of the Slinky, at the point where they meet, we momentarily get complete cancellation.

    3. *Constructive interference* takes place when two pulses add up, *destructive interference* is when they cancel each other out.

    4. Think about how dramatic destructive interference is: We would never have two particles coming together, briefly disappearing from the universe when they meet, then reappearing after their interaction.

VI. No matter where we look in nature, we see oscillatory motion—the behavior of waves. Next we'll talk about some more specific examples of waves.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Wave on a String. You can use this sim to help answer several of the questions below. With this sim, you can also explore reflections, pulses, and the relationship between wavelength and frequency and learn about what affects wave speed. Also try Masses and Springs to learn about simple harmonic motion. Sound is a good simulation to get a sense of the propagation of waves and the geometry of interference in two dimensions. Going a little further afield, you can investigate the mathematics of sine waves with Fourier: Making Waves.

Essential Reading:

Hewitt, chapter 18.

Thinkwell, "10: Oscillatory Motion" (first segment on simple harmonic motion) and "11: Waves: The Basics of Waves."

Recommended Reading:

Crease, chapter 4 and start of chapter 6.

Questions to Consider:

1. If you stretch a Slinky and wiggle one end, a pulse or wave will travel along the Slinky. What must you do to change the traveling speed of this wave? What is it about the wave that changes if you wiggle your hand faster? (The answer might surprise you. Give it a try. If you can't find a Slinky, go to the Wave on a String simulation and see if that helps you answer the question.)

2. Can you devise a real or simulated experiment to convince yourself that two pulses traveling oppositely on a Slinky combine to make a doubly big pulse? What happens if the two pulses are not the exact same shape?

3. How many examples of oscillations can you think of in everyday life? Are they all pure SHM, or are some oscillations more complicated? (Is the motion of a piston in your car engine SHM?)

4. Can two traveling waves, moving in opposite directions, reflect off of each other? Why or why not?

5. If two waves head toward one another with opposite "signs," they destructively interfere at the point of intersection. Does this mean that some energy was temporarily destroyed, only to reappear later (when the waves continue along)? If not, where did the energy go at that special point?

Lecture Twenty
Sound Waves and Light Waves

Interference in ordinary language usually suggests opposition or hindrance, but in physics we often do not use language the way it was originally designed!
—Richard Feynman, from *The Feynman Lectures in Physics*, vol. I

Scope: What do physicists mean when they say that sound is a wave or light is a wave? In this lecture, we will consider this question. Newton (of course!) was one of the founders of modern optics. Although he conceived of light as a stream of particles, his classic and beautiful experiments with prisms and optical lenses led to both theoretical and practical understanding of light that lasted for a century. More than 100 years after Newton, Young turned the world of optics on its head when he convincingly and dramatically demonstrated that light was *not* made of particles but was, in fact, a wave phenomenon. Maxwell's theoretical triumph 50 years later, showing light to be an electromagnetic wave, tied the story off neatly. Showing that Newton was wrong about *anything* is inevitably "revolutionary" but in a very different way than Newton's "revolution" from Greek natural philosophy; Young's revolution altered and deepened our conceptions of physical phenomena without breaking the structure of physics itself.

Outline

I. What do we mean when we say that sound is a wave?

    A. Consider first a model for sound waves propagating in a medium, in this case, air.

        1. Think of air as a collection of tiny, independent particles, like superballs, flying around the room and bumping into one another and the walls.

        2. If you clap, you compress these superballs locally, creating a region of high pressure. The superballs will push against their neighbors, which in turn, extends the high-pressure region. The result is a traveling wave of compression, a disturbance of the pressure of the air itself.

    B. The alternative to this wave model of sound might be one in which clapping results in the release of some kind of particles of sound.

II. What experiments could we do to determine which model of sound—the particle model or the wave model—is more accurate?

    A. We might, for example, try to measure the speed of sound, but doing so would not allow us to conclude whether we were dealing with particles or waves.

    B. At an outdoor concert, you might notice that even though you are some distance from the musicians, you still hear low frequencies and high frequencies at the same time.

        1. This suggests that sound is a wave because, as we learned in the last lecture, both high- and low-frequency waves travel at the same speed.

        2. If sound had a particle nature, we might think that high-frequency sounds would correspond to higher energies, which would mean that these particles would travel at higher speeds.

        3. This argument is compelling, but not completely convincing, for determining which model is correct.

    C. Waves should be "wavy"; that is, if sound is a wave, it should, for instance, bend around corners, and in fact, it does. You can easily hear someone in another room even if the room is around a corner from where you are. Still, sound might be particles bouncing out of the room, through the doorway, and around the corner.

    D. To test our model, we might set up an experiment with a microphone, which is nothing more than a little flap of material that moves with the alternating high pressure and low pressure of sound waves. The microphone converts the motion of this little flap into a voltage.

        1. We could watch the output of the microphone on an oscilloscope, and we would see the beautiful sine wave pattern that we talked about in Lecture Nineteen.

        2. Is this proof that sound is a wave? Not completely, because sound particles might be striking the flap, which then "rings" like a bell.

E. As mentioned in the last lecture, the most distinctive feature of waves is the characteristic of interference. How could you observe this characteristic with sound waves?

  1. You might set up two speakers, one in front of you on the left and one in front of you on the right. You stand at a point equally distant from both speakers while they both broadcast the same steady tone with the exact same loudness and pitch. At low frequencies, you can actually see the cone of the speaker moving in and out, but this is still not proof that we're dealing with waves.

  2. You might then reverse the wires on one speaker so that when one speaker is pushing out, the other is pulling in; the speakers would be precisely out of synch, or *out of phase*.

  3. In the wave model, when a speaker is pushing out, it's creating high pressure, and when it's pulling in, it's creating low pressure. Because the sound waves started out of phase and travel an equal distance to you, they will still be out of phase, and they will destructively interfere at all times. You should hear nothing.

  4. In the particle model, the speakers spew out sound particles, whether they are in phase or not. The sound you hear, then, should be twice as loud.

  5. Amazingly, if you performed this experiment (which is a little tricky), you would find that you could be standing in a room with two speakers broadcasting and hear silence. Audiophiles take this effect into account when setting up speakers in their homes.

F. We can also think of another experiment that might decide the question of whether sound has a wave nature or a particle nature: What if we remove the medium in which sound propagates (air)?

  1. If sound is a pressure wave in air, then without air, there can be no wave. But if sound is made up of particles, the particles should still be able to travel through a vacuum.

  2. This experiment was performed in the 1600s. Today, we could put a bell inside a jar and pump out all the air. As the air is removed, we could see the clapper of the bell moving, but we wouldn't be able to hear any ringing.

G. No single experiment proves the hypothesis that sound is a wave, but we have seen that sound is not particles. The wave model seems to be consistent, and it enables us to make predictions about what will happen in our experiments.

III. It is more difficult to conceive of light as a wave.

  A. This difficulty stems from the fact that the wavelength of light is very small, less than a micrometer. In contrast, the wavelength of sound is on a more human scale and is noticeable, as we saw when we talked about the room with two out-of-sync speakers.

  B. Newton believed that light was made up of light particles, which is not a completely illogical hypothesis. Recall that sound can bend around a corner; you can hear a person in another room around a corner from where you are. But you can't see a person in another room unless that room is directly in front of you. This seems to be evidence that light is not a wave. (We now know that the smaller the wavelength, the less waves tend to bend around corners.)

  C. In 1801, Thomas Young conducted a dramatic experiment in which he managed to see two light waves canceling each other out, much as we saw with sound waves in our speaker example.

  1. Young used a bright light source, with the light passing through a partition into which he had cut a narrow slit. As the light passed through this slit, it spread out in all directions and illuminated the far wall uniformly. This setup is the equivalent of creating a point-like source of light.

  2. Next, Young cut two slits in the far wall (this is the *double-slit experiment*). The expanding waves of light striking those two slits are symmetrical. Thus, the light at the two slits would be in phase (*coherent*).

  3. Two expanding waves of light now travel through the back side of the double-slit partition, and there are now places further along in the room where they add up and other places where they cancel.

  4. The result is a classic interference pattern—alternating bright and dark spots in a pattern exactly predictable from the wave model. Further, we can predict what would happen if we changed the color of the light, the number of slits, or the spacing of the slits.

  D. Young's experiment clearly proved that light is a wave, because only waves exhibit this kind of "destructive interference." But a puzzle remained: What is "waving"? As we've discussed, Maxwell solved this puzzle 50 years later with the idea that light is an electromagnetic wave—that is, electromagnetic fields waving in strength.

E. As we've seen with other fundamental ideas of physics, once we know that light and sound are waves, we can begin to find practical applications for this knowledge, such as sound-canceling headphones and anti-reflective coatings on glass.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Sound (particularly the Two Source Interference and Varying Air Pressure tabs, both of which will help you with the questions below); also try Quantum Wave Interference.

Essential Reading:

Hewitt, chapters 19 and 28.

Hobson, start of chapter 8

Thinkwell, "11: Waves: Waves on Top of Waves," "11: Sound," and "11: Interference."

Recommended Reading:

Crease, chapters 4 and 6.

Questions to Consider:

1. If you know that energy is being transmitted from one place to another, what sort of experiments can you think of to determine whether the energy was being carried by particles (material bodies) or by waves?

2. Give two reasons why sound waves decrease in strength as they move away from the source. How would this compare to electromagnetic waves leaving a source in empty space, and how would *that* compare to electromagnetic waves leaving a source in a region containing material (such as gases or glass)?

3. If you have a computer with a sound card, go to the Sound simulation at http://phet.colorado.edu and look at the tab for Two Source Interference. The listener starts at the exact midpoint. Do the two sound waves add up or cancel out? Move the listener around. Can you find the quiet spots where destructive interference is taking place? What can you say about the location of those spots? (How does the location depend on the frequency of sound?) Can you explain what is going on with the physical air (and air pressure) at those quiet spots?

4. Go to the Quantum Wave Interference simulation Start with photons, and turn the intensity and screen brightness up high. Choose Double Slits; make the slit width as small as possible and make the slit separation as wide as possible, with the vertical position in the middle somewhere (so that you're basically doing Young's experiment!) If you believed that light was a stream of particles, and you shined light from a pinpoint through *two* holes, what pattern of light would you expect to see on a far wall? Where would it be bright, and where would it get darker? Is there any reason to expect the light to be bright at a spot *directly behind the wall* at the center, that is, exactly between the two slits? Shouldn't that be a dark shadow? How does the wave nature of light explain the brightness right there at the midpoint?

Lecture Twenty-One
The Atomic Hypothesis

If, in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or atomic fact, or whatever you wish to call it) that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence you will see an enormous amount of information about the world, if just a little imagination and thinking are applied.
—Richard Feynman, from the *Feynman Lectures in Physics*, vol. I

Scope: In the first part of this course, we looked at fundamental, underlying principles of physics, explored particular forces, and saw that electricity and magnetism were unified and that the resulting force—electromagnetism—helps us to understand light and light waves. There's one more important part of the story—the idea that the world is made of atoms, independent, fundamental building blocks of matter. We'll trace this idea's long and complex history, which offers a unifying principle greater than Maxwell's equations. Energy, the structure of materials, chemistry, heat, optics, and more become tied together and often relatively simple to describe and explain at a fundamental level, once we have a basic understanding of atoms.

Outline

I. Greek natural philosophers debated what the world is made of.

   A. In about 400 B.C., Democritus (c. 470−380 B.C.E.) promoted a fairly modern idea of atoms: that at a fundamental level, the world is made of "uncuttable" (*atomos*) objects.

   B. Aristotle (384−322 B.C.E.) disagreed; his worldview encompassed qualities, which would be infinitely divisible.

   C. At the time, this was a philosophical, not a scientific, debate; people didn't consider measurable consequences of one idea versus the other.

   1. A stick of butter is a material that has certain defining characteristics: it's yellow, it melts at room temperature, and so on. If I cut the stick of butter in half, it's still butter; I haven't changed the essential character of it. I could continue this process of cutting the butter in half, and all along, I would still have butter.

   2. Democritus argued that at some point, I would reach an extremely tiny piece of butter that I could no longer cut. As we said, Aristotle disagreed with this idea. (For him, it's "butter all the way")

   D. To decide this question, we must consider the consequences of both theories.

II. Atoms are observable with modern equipment, such as a scanning electron microscope. Even in the 1700s, however, people were becoming convinced that the idea of atoms was a useful and correct description of nature.

   A. An atomic worldview is quite consistent with the classical physics ideas of reductionism and determinism, yet it also forms a bridge to modern ideas. In fact, I would argue that the classical physics story ends with the atomic theory; modern physics then takes over, looking at what the atom itself is made of. Even without the atomic worldview, much of classical physics still "works."

   B. According to the atomic hypothesis, there are about 100 different kinds of atoms, such as carbon, nitrogen, oxygen, hydrogen, and so on, that combine to form all material objects—solids, liquids, and gases.

   C. If we know the mass of the atoms and their interactions with other atoms, we can build (and understand) any material substance.

III. The idea of atoms helps us make sense of both physics and chemistry.

A. In Newton's era, alchemy served as a sort of proto-chemistry. Alchemy involved experimentation with materials, but it was practiced in secret and had a mystical aura.

B. Antoine Lavoisier (1743−1794), a French chemist working at the end of the 18th century, took the first classically scientific steps in chemistry. He showed, for example, that mass is conserved in chemical reactions, which tended to confirm the atomic hypothesis.

C. John Dalton (1766−1844), a British chemist working soon after Lavoisier, is called the father of the atomic model. He carefully studied many aspects of chemistry. Let's look at one example: forming water.

1. Mixing 2 parts (by mass) of hydrogen with 16 parts (by mass) of oxygen yields 18 parts of water vapor.

2. Looking instead at volumes, the combining ratios are 2 volume elements of hydrogen and 1 volume element of oxygen to yield 1 volume of water vapor. This makes sense if water is H_2O, that is, if a water molecule has 2 parts hydrogen for every 1 part oxygen.

D. In the end, the atomic model is a simple and elegant system that allows us to organize the elements and make sense of their properties.

IV. The experimental and theoretical work of Robert Boyle (1627−1691) in the late 1600s, Jacques Charles (1746−1823) in the late 1700s, and Amedeo Avogadro (1776−1856) in the early 1800s followed a parallel path toward the atomic hypothesis, this time, from the perspective of physics.

A. Instead of combining elements and looking at ratios and masses, these investigators were doing physics, that is, measuring forces, pressure, temperature, and so on. They found that the atomic hypothesis of chemistry helped them make sense of the physical properties of gases.

B. All gases have some universal characteristics. For example, they obey the *universal gas law*, or *ideal gas law*, which involves a relationship of pressure, volume, and temperature.

C. The atomic hypothesis characterizes a gas as a collection of atoms, independent "superballs" flying around in space. Pressure, then, results from these objects bouncing off the walls. This is an extension of the atomic hypothesis, a branch of physics called *statistical mechanics* (used in the explanation of atomic systems).

V. The atomic model leads us to much deeper questions about nature.

A. What makes a solid substance melt? The atoms in a solid state are bound together by chemical forces. As the substance is heated, the atoms gain kinetic energy; when the energy reaches a certain point, the chemical bond is broken and the atoms are free to move around. The result is a liquid, but note that in a liquid, the atoms are still in contact with one another. If the substance is heated still more, the atoms reach an energy level at which they lose contact, becoming a gas.

B. What makes a substance dissolve? Sugar stirred into water seems to disappear—where did it go? The atoms making up the sugar migrate into the spaces between the water molecules.

C. These are qualitative questions about atoms, but we might also begin to ask quantitative questions. For example, how big are atoms?

1. To answer this question, Benjamin Franklin conducted an experiment in which he placed a drop of oil onto a pond. By equating the volume of the drop to the volume of the resulting oil slick, Franklin came up with an estimate of the height of the slick, very roughly 1 atomic diameter, about a billionth of a meter.

2. The size of an atom can also be measured by a technique called *X-ray interference* and is comparable to the wavelength of X-rays.

D. The atomic hypothesis also helps us understand temperature (a measure of the energy of atoms). We'll explore this idea in the next lecture.

VI. Atoms are somewhat abstract to us because no one has ever seen one and no one ever will (they are much, much smaller than the visible wavelength of light). By now, however, atoms are a well-established idea in

physics. We can see the consequences of the atomic worldview all around us, enabling us to explain and calculate the properties of ordinary objects.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Gas Properties to study the ideal gas law and get a visual sense for how the atomic model is directly responsible for the observables, such as temperature and pressure. Balloons and Buoyancy may help you understand *why* a hot air balloon rises, based on the atomic model. For further investigation, check out any of the sims in the Chemistry category.

Essential Reading:

Hewitt, chapter 10.

Hobson, chapter 2.

March, chapter 13.

Recommended Reading:

Cropper, chapter 13.

Feynman Lectures, introductory chapter on atoms.

Questions to Consider:

1. What does the atomic hypothesis predict will happen to gas pressure as you increase its temperature? (Temperature measures the average kinetic energy of atoms, and pressure is related to the force the atoms apply to the walls. If you increase energy, what happens to the force atoms apply to the walls? What happens to the frequency at which atoms bounce off the walls?)

2. Which has more atoms, 1 kg of nitrogen gas or 1 kg of hydrogen gas? (Note: Hydrogen atoms are the lightest possible atoms. Nitrogen atoms are 14 times heavier than hydrogen.) Which has more atoms, 1 liter of nitrogen gas or 1 liter of hydrogen gas? (A liter is a measure of volume, not mass.)

3. Copper atoms have a mass of 63 *atomic mass units* (each *amu* is 1.66×10^{-27} grams). Estimate the mass of a penny. (A stamp scale can help. Otherwise, can you think of a way of comparing an unknown mass to known masses, for example, with a pile of pennies?) From that, estimate the number of atoms in a penny. Now estimate the volume of a penny (if you don't have a ruler to measure something as small in thickness as a penny, could you come up with a trick by stacking pennies to make an estimate?)

   Given the total volume and your estimate of the number of atoms, what is the volume of one atom? Assuming that the atom is a little "cube," what is the size of the atom? (Your answer should come out to be around 10^{-9} meters on a side.) If you look at a periodic table (go to the Web!), you can find atomic masses of all elements. Make a similar estimate for other materials you find in your house. Is the size of all atoms about the same?

4. Thinking more about the previous question. How could you figure out the mass of a single copper atom (without looking it up in the periodic table)? In other words, how did people figure out the mass numbers in that table?

Lecture Twenty-Two
Energy in Systems—Heat and Thermodynamics

Thermodynamics is the only physical theory of universal content which, within the framework of the applicability of its basic concepts, I am convinced will never be overthrown.
—Albert Einstein.

Scope: So far in these lectures, we've tried to simplify as much and as often as possible, before adding complexity back in by degree. Historically, this strategy has been extremely productive in physics and continues to be used to this day. In this lecture and the remaining ones in the course, we'll make the transition from simplicity to the recognition that the world is constructed of atoms, and thus, even simple things may be enormously complicated. We'll look at the field of thermodynamics, the study of heat and temperature, which requires an understanding of microscopic internal degrees of freedom exhibited by atoms. The physics of thermodynamics is everywhere–we use it in heating and cooling our homes, cooking food, taking the temperature of a child with a fever, and predicting the melting of glaciers. Thermodynamics is an appropriate ending topic for this course because it pulls together all the "big ideas" of classical physics, including Newton's force laws, energy principles, the atomic hypothesis, and statistical mechanics.

Outline

I. Thermodynamics begins with a focus on energy flow using the principles of statistical mechanics (which amounts to "averaging over atoms").

    A. Complex, real-life systems involve astronomical numbers of particles. A pot of boiling water might contain a million billion billion molecules.

    B. The reductionist viewpoint tells us to focus in on individual particles and track their reactions with regard to Newton's laws. This would be a hopeless task (given such a large number of particles to track).

    C. Instead, statistical mechanics tells us to think about averages—the behavior of *typical* atoms—without worrying about the details. This simplifies the story enormously.

    D. Insurance companies use this principle when they make predictions about when people will marry, have children, or die. It's not possible to make such predictions about individuals, but it is possible to do so for a large pool of people.

    E. Because atoms are simpler than people, predictions about average quantities are all the more reliable.

II. Thermodynamics is characterized by three laws, plus a starting (*zeroth*) law. The zeroth and first laws, which we'll look at in this lecture, are about work and energy, along with energy flow. The second and third laws add a new concept that we'll talk about in the next lecture—*entropy*.

III. The history of thermodynamics dates back to antiquity.

    A. Early ideas about heat included the *caloric theory*, in which heat was a material substance (a physical fluid) associated with high temperatures.

    B. The basis for the modern model of thermodynamics came from James Joule, whom we discussed in an earlier lecture. He articulated the idea that heat is the flow of thermal energy.

        1. Recall that energy comes in many forms—kinetic energy, gravitational potential energy, chemical potential energy, and so on.

        2. Think about a book sliding across a table. It starts with pure kinetic energy—energy of motion.

        3. When friction grinds the book to a halt, where did the energy go? It is not stored in an obvious way, as you might see in a compressed spring.

        4. With the atomic hypothesis, we know exactly what happened to the energy. The friction caused an increase in the motion of atoms in the book and table; thus, they have more kinetic energy. The thermal energy is stored in random kinetic energy of these atoms.

5. Thermal energy is measured in joules, just like any other kind of energy; we could measure quantitatively the thermal energy of the book and the table.

C. Experiments in thermodynamics were difficult to conduct, and progress in this field of physics was slow.

    1. These ideas might have been accessible to Newton, but it took almost 200 years to put the story together carefully.

    2. Part of the problem was that it's difficult to isolate a system thermally. It's also difficult to measure small temperature changes accurately, and older thermometers tended to interfere with scientific analysis.

D. Many physicists worked for years to make a convincing case that thermal energy is, indeed, just another form of energy, not some mysterious caloric fluid.

    1. We can think of some simplistic arguments against the caloric theory. For example, if you have a cup of coffee that is heated by the "caloric," it should weigh less as it cools off and the caloric leaves it.

    2. Suppose you have a block of dense material, and you want to drill through it. You know what will happen: As the drill bit grinds away, it will get hot. But where is the caloric coming from in this system? Is it created out of nothing by the interaction of two cool objects?

    3. Ultimately, many experiments verified Joule's idea that heat was not a material substance but related directly to energy.

IV. The zeroth law of thermodynamics defines *thermal equilibrium*.

A. Two objects in contact with each other may or may not be in thermal equilibrium. If they're not, they will change; one of them will cool off and one of them will warm up until nothing more happens. The two objects are then in thermal equilibrium.

B. The zeroth law of thermodynamics says that if object A is in equilibrium with object B, and object B is in equilibrium with object C, then A is in equilibrium with C. This is a practical statement, allowing us to use thermometers reliably.

C. Temperature becomes meaningful with the zeroth law of thermodynamics, and the law tells us that we measure temperature by comparison with a standard.

D. Microscopically, the zeroth law also makes sense. Temperature measures the average kinetic energy of the atoms in a system. The atoms in my body have a certain average kinetic energy; when I take my temperature, the thermometer reaches thermal equilibrium with my body.

    1. If the thermometer starts off cooler than my body temperature, its atoms are moving more slowly.

    2. What happens if we bring two solid objects into contact, one of them with atoms moving slowly and one of them with atoms moving rapidly? The atoms that are moving rapidly will bump into the slow ones more frequently and speed them up. Of course, the atoms that were moving rapidly will also slow down in the process.

    3. In the end, in equilibrium, the *average* energy of all the atoms will be the same.

    4. Temperature has nothing to do with the material object involved; it is nothing more or less than the average kinetic energy of atoms.

V. The first law of thermodynamics is a statement of energy conservation for complex objects.

A. To understand this idea, we need to define our vocabulary: *temperature*, *thermal energy*, and *heat*.

    1. *Temperature* is a measure of the average kinetic energy of particles.

    2. *Thermal energy* refers to the sum, not the average, of internal kinetic energies.

    3. In physics, *heat* is used as a verb, not a noun. Heat is defined as the transfer of thermal energy from one object to another.

B. The first law of thermodynamics says that energy is conserved.

    1. Total change in thermal energy arises from work plus heat.

    2. If you put a pot of water on a hot stove the water will get hotter. That means that the average energy of atoms is increasing; where is this energy coming from?

    3. A classic Newtonian concept is that energy is transferred through work. Thus, *stirring* the water would be one way of increasing its temperature

4. In our scenario, though, we are transferring random motion of the atoms on the stovetop and converting that to random motion of atoms in the water. (So here, we increase the temperature of the water by heating, *rather* than by doing mechanical work.)

5. Joule argued that heat and mechanical work are equivalent; they can both be measured in the same way. In fact, he measured the *mechanical equivalent of heat*.

C. The bottom line so far is that objects can hold thermal energy (hidden, *internal energy*), but this energy is fundamentally no different than any other kind. Up to this point, thermodynamics is a bookkeeping tool that allows us to keep track of energy. In the next lecture, we'll talk about the entropy concept, which will take us beyond bookkeeping.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Gas Properties again. Click on the Energy Histograms box and see if you can make sense of the resulting graphs!

Essential Reading:

Hewitt, first half of chapter 17.

Hobson, start of chapter 7.

Recommended Reading:

Hewitt, chapters 13–16.

Cropper, chapters 6–8.

Questions to Consider:

1. A metal and a wooden object sit in the same room for a long time. Which one has the higher temperature, or are they the same? Why? In which one do the atoms have a higher average kinetic energy, or are they the same? Why? Now touch them; the metal one will *feel* cooler. Can you make sense of this, given your (probably correct) answer to the previous question?

2. What happens to the work done when you vigorously shake the orange juice you're mixing up?

3. When you put an ice cube in hot water, does temperature "flow" between the ice and the water? (If not, what does flow between them?)

4. Does a ceiling fan cool the air in a room? If not, why do you use one? What is it doing?

5. Use the principle of conservation of energy to explain why the temperature of the air in a bike pump increases when you compress it, but the temperature of compressed gas in a can decreases when you let the gas suddenly expand.

6. Can you convert internal (thermal) energy into useful (mechanical, kinetic) energy? If so, give some examples.

7. Use the first law of thermodynamics to explain why the total energy of an *isolated* system never changes. Does that mean that "nothing interesting" can ever happen to an isolated system?

Lecture Twenty-Three
Heat and the Second Law of Thermodynamics

The law that entropy always increases—the second law of thermo-dynamics—holds, I think, the supreme position among the laws of physics. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experimentalists do bungle things from time to time. But if your theory is found to be against the Second Law of Thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

— Sir Arthur Eddington.

The Laws of Thermodynamics:
First Law: You can't win.
Second Law: You can't break even.
Third Law: You can't get out of the game.
— A popular (and fairly accurate) scientific joke

Scope: Thermodynamics began as an application and extension of the basic idea of energy conservation, and the first law of thermodynamics is a mathematical statement about conservation of energy. The most significant application of thermodynamics in our lives is a *heat engine*. This is a generic term for a device or system that converts thermal energy into useful work. In order to discuss heat engines, we will need to look at the concept of *entropy*, an abstract, elegant, and powerful property of systems. Entropy can be defined in several ways, related to heat flow and temperature or to "randomness." The implications arising from entropy considerations are profound and practical, expressed colloquially as "You can't win, you can't break even, and you can't get out of the game." Entropy and the laws of thermodynamics help us understand why heat engines are limited in efficiency (and why perpetual motion machines are impossible), despite all the creativity and best efforts of engineers and inventors. These principles describe the natural tendency of isolated systems toward states of more disorder and even touch on the direction of the "arrow of time."

Outline

I. Let's begin by exploring some of the broad properties of heat engines.

    A. A heat engine has a working material, a hot reservoir to take in thermal energy, and a cold reservoir to release thermal energy. The working material (for example, gas) converts thermal energy from the hot reservoir into mechanical energy. An example would be a car engine.

    B. A heat engine can also extract thermal energy from a cold reservoir and exhaust it to a hot reservoir. An example of this would be an air conditioner or refrigerator.

II. By the 1800s, people were using the principles of heat engines to build steam engines, but the engines exhibited poor efficiency.

    A. We can define *efficiency* as "what you get" divided by "what you pay for." For an engine, "what you get" is the amount of mechanical energy provided by the device; "what you pay for" is the amount of energy put into the device, measured as chemical potential energy.

    B. With conservation of energy, we know that "what you get" can never be greater than "what you pay for." In other words, according to the first law of thermodynamics, the efficiency of a heat engine can never exceed 1.

    C. In practice, if you put 1000 joules of stored chemical energy into a car in the form of gasoline, you might get 200 joules of useful work (kinetic energy) out of the system, for an efficiency of 20%. The remaining 800 joules is in the form of exhaust heat, a thermal energy increase of the cold reservoir (which in this case is the atmosphere.)

III. The second law of thermodynamics tells us that the maximum efficiency of a heat engine is generally much less than 100%.

A. This law was discovered by Sadi Carnot (1796–1832), a French engineer working with steam engines around 1800. Carnot was able to think about the fundamental principles governing steam engines, looking beyond the details of what fuel was used or what materials the engines were made of.

B. Carnot recognized the simple fact that, in an isolated system, hot objects always spontaneously cool down and cold objects always spontaneously warm up until they reach equilibrium.

C. Why does this principle never work in reverse? With two objects, why doesn't the hot one get hotter and the cold one get colder? Such a phenomenon could still conserve energy: The total thermal energy of the hot object would increase, but the total thermal energy of the cold object would decrease. The fact that this doesn't spontaneously happen *is* the second law of thermodynamics.

D. Carnot recognized that the second law had many concrete consequences.
   1. The maximum efficiency of a heat engine is determined by the temperatures of the hot and cold reservoirs.
   2. For a steam engine operating with fuel (boiling water) at 100° C and exhausting to room-temperature air, the maximum possible efficiency is a depressing 20%.
   3. This is a fundamental law of physics, and no heat engine, no matter how well engineered, can beat this limit.

E. The statistical mechanical view, which we'll discuss in a few moments, helps us see this law even more clearly; the second law arises from how atoms move and rearrange themselves, and there is no way around it.

IV. The second law of thermodynamics can be stated in many different ways. The concept of *entropy* is a way of reframing the second law.

A. Entropy is a measurable quantity of systems, much as energy is. The statistical mechanical worldview teaches us to think about entropy microscopically as a measure of randomness. The more orderly a system is, the less entropy it has and vice versa.

B. What do we mean by *randomness*? Microscopically, the term refers to how many "states" are available in a system.

C. Adding energy is one way of increasing entropy, but the two are not the same properties.

D. The second law of thermodynamics is a counting argument, based on pure probability.
   1. If you buy a new deck of cards, it is highly ordered (low entropy). When you shuffle the deck a number of times, the cards will become more random (increasing entropy), but you will never, in your lifetime, shuffle the deck back into its original ordered state.
   2. With 52 cards, there is an absurdly tiny chance that the cards could be shuffled back into order, but with a million billion billion atoms in a pot of water, the chance of entropy spontaneously decreasing through natural events is 0 to any degree of approximation!

E. We can see this in relation to Carnot's statement of the second law of thermodynamics.
   1. In isolated thermal systems, hotter objects get cooler and cooler objects get hotter.
   2. If we're thinking about entropy, the cooler object could not become even colder, because that would be an increase in entropy. (Colder objects tend to be more orderly.)

V. Once we think about thermodynamics in this way, that is, with regard to systems and their natural evolution, we realize that some forms of energy are more *useful* than others.

A. More useful energy has less entropy. Every molecule in a car traveling down the highway is going in the same direction with the same average speed. This system is about as orderly as we can imagine, and the state is one of very low entropy for that amount of energy to be configured in. If the car crashed, the energy would be conserved, but the thermal energy would be in a much more random state.

B. This tells us why engines have a maximum efficiency. The hot gases in a car engine are in a state of random thermal energy. The engine extracts some of that energy to drive the car, but all of the energy cannot be transferred to motion of the car, because that would violate the second law of thermodynamics. Converting all the random thermal energy in the gas to kinetic energy of the car would decrease the overall entropy of the system.

VI. The second law of thermodynamics does not say that entropy never decreases. It says only that entropy of *isolated systems* never decreases.

   A. When you put water in the freezer, the water molecules spontaneously freeze, becoming ice. That's moving to a state of more order, or lower entropy, but it happens because the water is not isolated; freezing the water requires external energy.

   B. Some people have argued that human beings are low-entropy systems. "Making" a human involves increasing the order of certain chemicals to form organs; locally, then, entropy is decreasing. As a baby is formed, however, the mother requires energy from outside systems, and at the same time, she is increasing the entropy of the environment by releasing waste heat. Overall, entropy in the universe is increasing!

VII. All of this leads to a philosophical question about time: As time goes by, entropy is increasing, and we always think of time as going forward. The "arrow of time" points in only one direction.

   A. Newton's laws don't tell us why time should go one way and not the other. Watching a movie of billiard balls colliding on a table, we couldn't tell whether the movie was running forward or backward. Newton's laws are *time reversible*.

   B. But thermodynamic processes are not time reversible. If we watched a movie of an egg falling to the floor and breaking (and heating the floor slightly), we would know very well whether the movie was running forward or backward. We know that we could never use the thermal energy from the floor to repair the egg and sending it flying back upward into a person's waiting hands.

   C. It's possible, then, that the direction of time is associated with the second law of thermodynamics.

Essential Computer Sim:

Go to http://phet.colorado.edu and play with Friction and Reversible Reactions.

Essential Reading:

Hewitt, second half of chapter 17.

Hobson, rest of chapter 7.

Recommended Reading:

Cropper, chapters 3, 9–10.

Lightman, chapter 2.

Questions to Consider:

1. Explain how the laws of thermodynamics are, in a sense, equivalent to the joke lines quoted at the start of this lecture. (We didn't cover the third law, so just focus on the first two.)

2. Can you come up with several examples of naturally occurring processes that show how high-quality (usable) energy degrades into lower-quality (internal, thermal) energy?

3. When you clean up a room, what is happening to the entropy (randomness) of the room? Does this process violate the second law of thermodynamics?

4. Think about watching a movie of natural events, but you don't know if the movie is running forward or backward. Come up with some events where you could not tell which way the movie was running and others where it would be obvious. Now think about entropy—does it help explain the difference between these classes of events?

5. If a company claims it will produce a new super-efficient gasoline-powered engine that will put out 200 horsepower (hp) steadily for an hour on 1 gallon of gas, are you interested in buying the company's stock (or its product), or should you report the company to the Better Business Bureau as scammers? (Useful data: One gallon of gas contains 36.6 kWh of stored chemical energy, and 1 hp is 750 watts.)

6. If a company claims that it can rebuild your carburetor to make your car 90% efficient at converting gas energy into energy of motion, are you interested, or are they scamming you?

Lecture Twenty-Four
The Grand Picture of Classical Physics

Poets say science takes away from the beauty of the stars— mere globs of gas atoms. Nothing is "mere." I too can see the stars on a desert night, and feel them. But do I see less or more? The vastness of the heavens stretches my imagination—stuck on this carousel my little eye can catch one-million-year-old light. A vast pattern—of which I am a part... What is the pattern or the meaning or the why? It does not do harm to the mystery to know a little more about it. For far more marvelous is the truth than any artists of the past imagined it. Why do the poets of the present not speak of it? What men are poets who can speak of Jupiter if he were a man, but if he is an immense spinning sphere of methane and ammonia must be silent?
—Richard Feynman, footnote in *The Feynman Lectures on Physics*

Before I came here I was confused about this subject. Having listened to your lecture I am still confused. But on a higher level.
—Fermi

Scope: Classical physics is defined in part, historically and, in part, by a philosophical mindset: The world is ordered, and there is a limited set of fundamental ideas that explain and predict all natural phenomena. The world is made of matter and energy, existing in space and time, with measurable properties and behaviors. These core ideas can be quantified via a small, consistent set of assumptions and mathematical relations, with enormous practical and predictive power. The specific ideas we have discussed form just part of what we mean by classical physics: force and acceleration as "cause and effect"; energy flow as an alternative tool for thinking about natural processes; gravity, electricity, and magnetism as fundamental forces; and matter made of atoms, with optics and thermodynamics as natural consequences. The universe in this framing is deterministic and "clock-like," with complex behavior understood by a reductionist approach to first principles. This approach to scientific truth is still widely used by scientists and others working in many fields, but it is not the "end of understanding," nor ultimate truth.

The developments of nuclear physics and radioactivity led to a totally new kind of mechanics, *quantum mechanics*, which approaches the world quite differently, with different assumptions about the "rules of the game," as well as the philosophy behind the game. The ideas of relativity challenge Newton's belief in a fixed, external space-time frame in which physics "occurs." But all of these developments remain consistent with, or connect tightly to, classical physics, which will always remain as one of our grand intellectual achievements.

Outline

I. Classical physics was firmly established by Isaac Newton and has undergone continuous development ever since.
   A. We might define classical physics by its dates, starting in 1687 with the publication of the *Principia* and working our way up to about 1900. This definition isn't entirely satisfactory because classical physics continues to evolve to this day.
   B. It's probably more productive to define classical physics in terms of its topics: mechanics of particles, forces of nature (gravity, electricity, magnetism), optics, thermodynamics, and so on. Classical physics also encompasses other topics, such as fluid flow or acoustics, that we haven't talked about in this course.
      1. These topics are often fundamentally about the world we live in—they apply to cars, bicycles, rockets, sports, architecture, and many other aspects of our lives.
      2. But classical physics also goes beyond everyday experience; with this study, we can understand particles down to a size of a billionth of a meter and up to the distance scales of our galaxy and beyond.
   C. We might also define classical physics in terms of its applications. This discipline is still studied by all scientists, as well as architects, engineers, and others.

D. To paraphrase Newton, we could say that classical physics is the giant on whose shoulders science stands today.

II. Classical physics is also, in part, a way of thinking about science, a scientific-philosophical vantage point.

A. A classical worldview is traditional and empirical: it says the world is real and exists independent of human beings; the goal of classical physics is to learn about this real world through experimentation and the development of coherent, unified theories.

B. A classical worldview is often reductionist, operating from the perspective that complex natural behavior can be described, explained, understood, and predicted by analyzing simpler components.

C. Related to the ideas that the world is real and reducible is the classical idea that the world is deterministic; that is, we can use our understanding of the world to make qualitative and quantitative predictions. In this view, our universe is similar to a giant clockwork.

D. Ultimately, classical physics postulates a small, cohesive set of underlying ideas. This set includes the kinematical ideas of position, velocity, and acceleration and the dynamical ideas of inertia, mass, force, momentum, and energy. It also includes some of the laws of nature that we discussed: Newton's laws, conservation laws (related to energy, momentum, angular momentum, and charge), and Maxwell's equations.

E. Finally, classical physics relies on the scientific method of investigation: observing the world, forming and testing hypotheses, and asking further questions.

III. Physics today has moved in new directions, to the realm of modern physics.

A. Albert Einstein (1879–1955) is the "hero" of modern physics, although he was, in much of his work, a classical physicist too.
 1. Einstein's theory of special relativity built on Galilean relativity, the idea that the *laws* of nature are invariant, independent of the reference frame of the observer.
 2. Combining this idea with Maxwell's equations, Einstein realized a radical truth: The speed of light is itself a law of nature, independent of the observer.
 3. Einstein saw that neither Galileo nor Newton was completely wrong, but our intuitive understanding of space and time—the Newtonian idea that space and time were fixed and universal and independent of the observer—required revision. For example, relativity requires us to redefine momentum and kinetic energy, for objects traveling at speeds close to the speed of light.
 4. In the same way, Einstein's theory of general relativity changed the way we think about gravity. It re-imagines space and time in a geometrical sense and gives us a new idea about what gravity is and where it comes from.

B. Beginning around 1900, the field of quantum physics began to delve deeper into the atomic hypothesis of classical physics.
 1. When physicists tried to understand the structure of atoms themselves, it became apparent that Newton's laws were insufficient to deal with distance scales of billionths of a meter or smaller.
 2. The theory of quantum mechanics was not just a "fix" of Newton's laws; it altered the fundamental premises of classical physics, including determinism.
 3. Classical physics assumes that if we understand enough about the world, we can make predictions about natural phenomena, such as the weather. With quantum mechanics, we find that many measurements, such as the time required for a particle to decay, are fundamentally uncertain and cannot be predicted.

C. Do these new discoveries completely unseat classical physics? Absolutely not. Classical physics describes the world we live in as accurately today as it did in the 1600s when Newton was first making sense of it. Modern physics *builds* on the underlying ideas of classical physics, expanding their bounds of applicability.

III. Classical physics has been one of the most fruitful, productive, and powerful intellectual endeavors in the history of civilization.

A. We study classical physics, not because we're interested in history, but because it still influences much of contemporary science and engineering.

B. We can also use classical physics as a tool to understand the science behind political issues involving energy or the environment.

C. As we close this course, I hope you will keep these ideas in mind and investigate them further in your everyday experiences.

Recommended Reading:

The world is your oyster.

Questions to Consider:

1. In what ways does physics connect to your personal life? Is your interest in physics intellectual, academic, practical, or some combination of these?

2. Modern physics has changed the philosophical outlook of scientists on many levels and challenges ideas as fundamental as the absolute nature of space, or the nature of atoms, or even Newton's laws. (For example, $F = ma$, force = mass $\times$ acceleration, is not useful or even completely correct, if you consider electrons inside an atom or objects traveling near the speed of light.) Given that, what is the value in studying classical physics?

3. Do physicists still "do" any classical physics? (Who else uses classical physics?)

4. What steps do you need to take to continue to satisfy your interest and curiosity in physics and science?

Biographical Notes

A biographical list of "key contributors" to the development of classical physics is almost impossible to compile because the number of contributors is so large! Although famous physicists often get sole credit for their accomplishments, the great discoveries are inevitably part of a web of scientific progress. Truly significant contributions come from both brilliant and more mediocre scientists, not to mention support from graduate and sometimes undergraduate students, technicians, lab assistants, and so on. Most of the discoveries in physics have a complex lineage; historians could (and do) quibble about the attributions and origins of almost every idea in the field. Some ideas get "rediscovered" or further developed, then attributed to the scientist who somehow was better able to spread the word. What follows is an extraordinarily abbreviated list of some of the *most* famous names in the field. The large number left out is painful to this "biographer" (who is also admittedly not even remotely a historian of physics).

It is also worth noting that the physics described in this course is directly descended from the Western European tradition, and it may seem culturally insensitive not to mention discoveries made by Asian, Native American, African, or Arabic science. This arises from a combination of the shameful ignorance of the author of this text and the nature of contemporary Western science education, in which there is a direct pedigree and narrative that flows through the Western tradition. By no means should we discount the discoveries that were made on other continents, but the historical story that sits aside conventional (Western) introductory courses in physics is predominantly European in nature.

Greek Philosopher-Scientists (600 B.C.E.–A.D. 150)

Western philosophy, including *natural philosophy* (the philosophical precursor to science) traces its roots back to the Greeks. Because this course deals with the Western tradition of physics, we need to mention the beginnings, even if only in passing, because it was the growth away from the ideas of the Greeks that has largely defined physics as we now know it.

Aristotle (384–322 B.C.E.). Aristotle's name is perhaps most important to modern science, not for the work he did, but as a symbol. Up until the 18th and early 19th centuries, the studies of philosophy and science were closely linked. Aristotle was the author of the philosophical and scientific system that was to dominate Western thought into the 17th century. Although he has a large body of work devoted to mathematics, philosophy, and zoology, the most pertinent of Aristotle's works for our course is his view on the motion of physical bodies.

Aristotle maintained that the speed of an object is determined by the magnitude of the force pushing it: The greater the force, the faster the body will move. Although initially quite plausible (and correct in situations where viscous drag dominates; indeed, this is one of the most common mistakes made by students in introductory physics courses!), this model breaks down when applied to astronomical bodies. It was the interpretation of the stars (first by Ptolemy, followed by Copernicus, Kepler, Galileo, and finally, Newton) that proved to form a more robust basis for the study of physical motion.

Aristarchus (310–230 B.C.E.). Aristarchus was a mathematician and astronomer who came from the same island as Pythagoras. Most of what survives of his work comes in the form of quotes from other writers of his era and a few indirect references. Still, he is often credited with being one of the initial proponents of a heliocentric model—one in which the Earth and other planets rotate about the Sun. The only surviving work of Aristarchus is *On the Sizes and Distances of the Sun and Moon*, which attempts to estimate the distances between the Earth, the Sun, and the Moon by cunning use of geometry.

Ptolemy (c. 85–165). Ptolemy was the proponent of the geocentric (Earth-centered) model of the solar system that was to prevail in Europe for 1400 years. Unlike those of most other classical authors, many of Ptolemy's works survived the trials of time and are available to us now in their original forms. Based on philosophical and scientific ideas, Ptolemy's model proposed that the Sun and all the planets rotated about the Earth, each having a complex system of "gears" (epicycles) that rotated at the same time in order to account for the motion that the planets exhibit in the nighttime sky. (The word *planet* is derived from the Greek word for "wanderer.") The Ptolemaic model of the solar system is impressively accurate, satisfying observational astronomy's needs until the "modern" high-precision observations of the late 16th and early 17th centuries.

The Birth of Classical Physics (1500–1800)

Nicolaus Copernicus (1473–1543). Copernicus was born in Poland, the son of a copper merchant. When Nicolaus was 10, his father died, and he and his siblings were placed in the custody of their uncle, a Church canon. Nicolaus was educated at the cathedral school, then enrolled in the University of Krakow, where he received an education in Latin, philosophy, mathematics, and (most importantly) astronomy. He became a canon, like his uncle, and continued his education throughout his life, adding Greek, medicine, and canon law to his list of accomplishments.

Copernicus is given credit for one of the first proposals of a Sun-centered universe since the classical age. He first proposed his ideas in a small handwritten book in 1514 that he circulated anonymously amongst his friends. Meanwhile, his other duties included advising the pope on calendar reform, organizing the defense of his hometown, and carrying out currency reform. It wasn't until the end of his life, in 1543, that he published his final theory of the heliocentric universe. His magnum opus was deliberately circumspect, presenting itself as a theory rather than the absolute truth and, thus, avoiding controversy and Church censorship. Although the details were still wrong (Copernicus assumed perfectly circular orbits for the planets), Galileo, Brahe, and Kepler all read this work and were profoundly influenced by it.

Tycho Brahe (1546–1601). Tycho Brahe was born into the Danish nobility; both his father and mother came from important families that were influential with the Danish king. At the age of 13, he began attending the University of Copenhagen, ostensibly to study law, but he soon discovered that his real passion was astronomy (helped along by an eclipse in 1560). As part of his studies, Brahe traveled on the Continent. In 1567, he was involved in an altercation with another Danish student while he was in Germany that resulted in part of his nose being cut off in a duel.

By the 1570s, Brahe had earned a reputation as Denmark's preeminent scientist. When he announced his intention to leave Denmark, the king offered him an island on which to build a royal observatory as enticement to stay. This observatory at Hven collected data on the position of stars in the sky to an unmatched degree of precision (without the use of telescopes, which were not yet in use for astronomical observations!). Brahe would pass on these data to Kepler, leading to Kepler's three laws of celestial motion. In 1588, the king who had appointed Brahe died, and Brahe was not in favor with the new monarch. He left his position in 1597 for Germany, where he was appointed imperial mathematician in 1599.

Brahe died at the age of 65. The (possibly apocryphal) story is that he died from a ruptured bladder, caused by his refusal to leave the table at a feast before his host did.

Johannes Kepler (1571–1630). Kepler was the son of a mercenary soldier and an innkeeper's daughter in what is now modern Germany. His father died in a war in the Netherlands when Johannes was 5 years old. The boy was schooled by monks and, throughout his life, was profoundly religious, seeing his work as part of the Christian duty to understand the works of God.

The contribution for which Kepler is most remembered is his development of the three laws of planetary motion. As imperial mathematician, Kepler inherited all the data collected by Tycho Brahe over the previous 40-year period. Kepler, through grueling hours of analysis (over the course of years), deduced the motion of the planets and discovered that it fit most accurately with the Sun-centered model of the solar system put forward by Copernicus, albeit with the critical modification that the planetary orbits are not ideal circles but elliptical paths. Furthermore, Kepler's analysis of the planets' motion in time allowed him to state three geometrical laws that appeared to describe the motion of *all* planets. It was the crowning achievement of Newton's law of gravitation that it was able to re-create and derive Kepler's observational laws from first principles.

Galileo Galilei (1564–1642). Galileo was the son of a musician living near Pisa, Italy. At a young age, he sought to join a monastic order but was forced to return home by his father, who had already decided that his son was to become a medical doctor. Over the course of his medical studies, Galileo was exposed to mathematics and natural philosophy, which he took to immediately. He slacked off in his other classes, devoting all his energy to those two subjects. By the age of 21, he had earned an appointment as a teacher of mathematics in Siena. By 1592, he was offered an appointment as a professor of mathematics at the University of Padua.

Although much of Galileo's work was in the area of engineering (he more than doubled the magnification of telescopes of the time) and astronomy (it is for him that the Galilean moons of Jupiter are so named), the work for which he is most famous is the *Dialogue of Two Chief World Systems*, which he published in 1630. This was framed

as a debate between the Copernican model of the heavens, which placed the Sun at the center and the other planets orbiting around it, and the Ptolemaic system, which placed the Earth at the center of the heavenly system. The confrontational manner in which he wrote this work earned Galileo censure by the Church.

Galileo is also perhaps the most famous figure associated with overturning the Aristotelian and Ptolemaic models of physics, in large measure because of his conflict with the Church. His work was extremely insightful, however, and inspired many future scientists, up to and including Einstein.

Isaac Newton (1643–1727). Newton is the father of physics, indeed, of all of modern science in many ways. I can think of few individuals of the last 1000 years with more direct and profound influence on the human condition. Isaac Newton's masterwork, the *Principia*, articulated not only a number of physical laws but also the scientific method itself. Newton's laws describe and (to some extent) explain motion and gravity. When faced with the need to solve the equations he developed, Newton *invented* the calculus required to solve them. His central laws are *universal*, applicable to any system in any circumstance. Even today, their accuracy and power is extraordinary. Although Newton's laws must be extended under extreme conditions (for example, for objects traveling near the speed of light), they still form the basis for much of modern technology. Newton was involved with both theory and experimentation, and his research touched on and formed the roots of many branches of modern physics, including optics, thermodynamics (heat), fluids, and more. Students in freshman physics learn about Newton's work in their first semester (then repeatedly, with further depth, as they progress). The metric unit of force, the *newton*, is named in his honor. Newton was not a pleasant or easy man. He had a big ego, never married, and had many disputes over intellectual priorities during his life. However, in an uncharacteristic but famous quote, he said, "If I have seen further, it is by standing on the shoulders of giants."

Henry Cavendish (1731–1810). Of all the 18th-century physicists, Cavendish was one of the most eccentric. He was pathologically shy—to the point of having a second staircase installed in his house so that he could avoid seeing his housekeeper. When invited to scientific salons (a fashionable dinner party featuring important figures in a field of literature or science), the only social event he would attend, people seeking his opinion were advised to enter the room, not look at him, and speak their questions to the opposite wall.

Because of his shyness, Cavendish rarely published, and later review of his work revealed that he had discovered many laws relating to properties of gases, chemistry, and electricity before others who were credited with their discovery. The published work for which Cavendish is best remembered (*Philosophical Transactions of the Royal Society of London*, 1798) was the extremely accurate and precise determination of the density of the Earth using an experiment designed by John Michell (who died before he could complete it). The experiment used a delicate torsional balance, as well as mirrors and optics, to measure the force between two large weights in the lab. The current results for the mass of the Earth deviate by only 1% from the results that Cavendish obtained more than 200 years ago. The result is now framed as the first measurement of the universal constant of nature (known as G), which appears in Newton's formula for the gravitational force between objects.

James Watt (1736–1819). Watt was born the son of a Scottish shipwright and was largely home-schooled by his mother. At the age of 17, he traveled to London to become an instrument maker and became the head of a small workshop at the University of Glasgow upon his return to Scotland. While at Glasgow, Watt became interested in steam engines (then in their earliest stages). After studying one that was in the possession of the university, he came up with a scheme to dramatically improve their efficiency, but the machining issues in creating a prototype, as well as finding funding for the effort, proved difficult, occupying Watt for nine years before he formed a partnership with Matthew Boulton.

Both Boulton and Watt made a fortune off the steam engines produced by their partnership. Watt is also given credit for inventing the steam locomotive in 1784. Although he was not a scientist by trade, it was Watt's inventions that drove an entire branch of scientific inquiry for the next 100. The improved efficiency of his new steam engine also opened the way for an industrial revolution powered by steam and coal, rather than by rivers and waterwheels.

Nicolas Sadi Carnot (1796–1832). Carnot grew up through the tumult of the French Revolution and the Napoleonic wars. He was home-schooled by his father in mathematics and science, as well as language and music. After studying at the École Polytechnique under such notables as Ampère and Poisson, Carnot enrolled in a two-year course in military engineering.

After leaving active duty in the military to attend more courses in Paris, Carnot began (in 1821) studying the mathematical theory of heat, which led to modern thermodynamics. He was driven by the problem of designing

more efficient steam engines. His name is now attached to the *Carnot engine*, an idealized device that mathematically proved the theory that ideal efficiency of a heat engine depended on the difference in temperature between the engine itself and the surrounding environment, not on the nature of the substance used in the engine.

Carnot died in 1832 at the age of 36, only a day after contracting cholera in an epidemic that swept Paris.

James Prescott Joule (1818–1889). The son of a wealthy brewer, Joule had an early scientific education (home-schooled for 16 years, then tutored by John Dalton of chemistry fame). Joule was active in running the family brewery until its sale in 1854, initially treating science as a hobby. When he began looking into replacing the brewery's steam engine with a new electrical engine, science began to occupy more of his life.

Initially ignored by the Royal Society of London as a provincial dabbler, between 1840 and 1850, Joule discovered the law that is named for him—showing the connections between mechanical energy and heat—and continually refined his experiments, improving the accuracy of the results (because the nature of his discovery demanded extremely precise measurements!).

Although there was a dispute with a German scientist, Julius Robert von Mayer, as to who was the first to determine the relationships among work, energy, and heat, the unit that modern scientists use for energy is named after Joule.

The Early Chemists (1750–1860)

Antoine Lavoisier (1743–1794). Lavoisier was a French nobleman whose contributions feature prominently in chemistry, biology, finance, and economics. He identified the element oxygen in 1779 and showed that respiration by living beings was essentially the very slow combustion of organic material inside the body. In 1783, he dethroned the phlogiston theory of combustion, the previous model by which chemical reactions were understood.

Lavoisier introduced the law of conservation of mass; that is, that in chemical reactions, matter is neither created nor destroyed but simply changes form. His *Elementary Treatise of Chemistry* is considered to be the first textbook of modern chemistry.

His accomplishments in science aside, Lavoisier was a prominent member of the French nobility and served as a tax collector. The French Revolution did not treat such people well, and in 1794, he was framed for treason and guillotined (he was exonerated by the French government a year and a half after his death).

John Dalton (1766–1844). John Dalton was born in Cumberfield, England, and educated by his father, a teacher at the Quaker school in the same town. At the age of 12, he assumed that post upon his father's retirement. Although his initial foray into teaching was a disaster, he kept at it and passed the majority of his life earning a living as a teacher, either at a public post or as a private tutor.

In 1800, Dalton became the secretary of the Manchester Literary and Philosophical Society, through which he proposed the major work that he is remembered for. Inspired by Lavoisier's work, Dalton proposed his atomic theory, that is, that all matter is made of tiny, indivisible atoms. Everything about a certain atom can be known by knowing what element that atom is—all atoms of one element are identical but are fundamentally different from the atoms of each other element. Dalton's atoms can be neither created nor destroyed and are only moved about in chemical processes.

In 1837, Dalton suffered an attack of paralysis and again in 1838. In early 1844, he suffered a stroke, and his last meteorological observation is recorded the day before he was found dead by an attendant in July 1844.

Amedeo Avogadro (1776–1856). Born to a noble Italian family, Avogadro graduated with a law degree and began practice at the age of 20. Soon thereafter, he became interested in physics and mathematics and, in 1809, began teaching both subjects at the high school level. While he was teaching, he first proposed what is now known as Avogadro's law—that gases of equal temperature, pressure, and volume (no matter what the gas is) contain the same number of molecules. *Avogadro's number* is named in his honor and refers to the number of atoms contained in 1 mole of substance (roughly 602 septillion—602,200,000,000,000,000,000,000—a very large number!)

Relatively little is known about Avogadro's personal life. He was given a post at the University of Turin in 1820 as a professor of physics. Though he was restricted from teaching for a time because of his political support of Sardinian revolutionary movements, he ultimately taught there until 1853, with only a brief hiatus.

The Exploration of Electricity and Magnetism (1700–1900)

Benjamin Franklin (1706–1790). Franklin is probably one of the most well-known classical scientists, after Newton and Galileo. His fame, however, comes mostly from his nonscientific pursuits (publisher, ambassador, revolutionary). In 1748, 15 years after publishing the first *Poor Richard's Almanac*, Franklin retired from the printing business to pursue other opportunities, scientific experiments being chief among them.

Franklin's most famous work was in the field of electricity. Scientists before Franklin had identified two different types of "electrical fluid," the "vitreous" and "resinous." Franklin was one of the first to propose that there weren't two separate fluids but that both were simply different manifestations of the same fluid—a concept we know today as electric charge. His famous kite experiment (whether Franklin ever actually performed it is uncertain) was designed to prove that lightning was electrical in nature by flying a kite in a storm and showing that it collected an electric charge. The practical application of this theory led Franklin to invent the grounding wire and the lightning rod. Franklin's writings were well received in Europe, and his fame as a scientist overseas played no small role in his becoming an ambassador to Europe for the colonies before and during the American Revolution.

Charles-Augustin de Coulomb (1736–1806). Charles Coulomb's father was a successful lawyer and administrator, while his mother came from a quite wealthy family. As a child, he was given the finest classical education, studying language, literature, and philosophy, in addition to more modern subjects, including mathematics, botany, chemistry, and astronomy.

Coulomb studied to be an engineer for the French army, becoming an expert in structural design, fortifications, and soil mechanics. While working as a military engineer, he wrote seven papers (between 1785 and 1791), in which he developed the theory of attraction between charges, describing both how the force decreased with distance and how positive and negative charges interacted. Though these were his most important works as far as posterity is concerned, Coulomb participated in more than 300 committees for the French Academy of Science and wrote 25 memoirs, in addition to collaborating with many other important French scientists of his era.

Coulomb survived the tumult of the French Revolution (including the dissolution of the Academy of Science and its re-creation as the French Institute) and spent the twilight years of his life as inspector general of public instruction, setting up schools across France.

Alessandro Volta (1745–1827). Volta grew up and was educated in Italy. He was a professor of physics in Lombardy for most of his life, primarily interested in the study of electricity. In honor of his contributions to science, he was given the title of count by Napoleon in 1810. It is for him that we name the unit of electrical potential energy (per unit charge), the *volt*.

Volta's most famous contribution to science was the development of the *voltaic pile*, a very early battery. Previously, electricity had been studied by building up charge on metal spheres (in the same way that scuffing your feet across the carpet on a dry day builds up static charge on you), then studying how it interacted with other charges. Volta's chemical battery allowed for a steady source of charge to be produced, making it possible to study charges in motion and at rest. Coulomb turned electric forces into testable laws in the same way that Newton and Cavendish had done for gravity. The voltaic pile paved the way for Oersted and Ampère to do the same for electrical currents, to find their connection to magnetism, and eventually, for Maxwell to fully unify the two forces.

Thomas Young (1773–1829). One of the contenders for the title "Last Man to Know Everything," Thomas Young's knowledge was broad and far reaching. He studied medicine and the optics of the human eye and was one of the first scholars to translate the Rosetta Stone, which allowed us to read Egyptian hieroglyphs. He was born as the youngest of 10 children to a Quaker family in England and, by the age of 14, was said to be able to read 12 ancient languages!

For physicists, Young's most famous work was his double-slit experiment, in which he passed a beam of light through two narrow slits and observed a diffraction pattern on a screen on the other side. Even in modern physics, the results of this experiment are used as one of the strongest pieces of evidence in favor of the wave nature of light, though it would take until Maxwell's equations to demonstrate just what light is a wave of.

André-Marie Ampère (1775–1836). A French scientist and professor, Ampère was one of the first and most successful to expand on Oersted's connection between electric and magnetic forces. Ampère's name is now attached to the law describing the interaction of currents, reducing magnetism to the result of the motion of small charge carriers. Ampère's ultimate legacy to physics is overshadowed by that of Maxwell, but he was a pioneer in the study

of electrodynamics, as Newton and Galileo were for mechanics (although he was not nearly so colorful a personality!). Although later scientists are given credit for more fully developing the theory, Ampère was one of the giants on whose shoulders they stood. Ampère spent the latter part of his career (after 1827) studying philosophy, which he considered "the only really important science."

Hans Christian Oersted (1777–1851). The name of this Danish physicist would likely be lost to obscurity were it not for happenstance. While preparing for a public lecture in 1820, Oersted noticed that a moving current caused a deviation of a nearby compass needle. After some intensive investigation, he published this discovery, which provided the impetus to other scientists (Ampère and Faraday foremost among them) to develop the mathematical and conceptual frameworks for understanding this phenomenon, culminating in the work of Maxwell.

Oersted's discovery would not have been so sensational except that it was in direct contradiction to the hypothesis of Coulomb, which had been taken as fact, that there categorically could be no interaction between electricity and magnetism. It took a direct repetition of the experiment, two months after the initial publication, in front of the French Academy for that body to accept the data as something other than blatant falsification.

Johann Carl Friedrich Gauss (1777–1855). Gauss's brilliance was revealed early: The story is that by the age of 7, he amazed his teachers by almost instantly summing all the numbers between 1 and 100 (by the trick of realizing that he could rearrange the numbers into 50 pairs that each added to 101 [1 + 100] + [2 + 99]…).

Gauss published works in both mathematics and practical astronomy, collecting observations used to further refine the known orbits of planets for 30 years. His mathematical work was concerned with differential geometry, inspired by an early job in surveying. Perhaps his greatest contribution to physics, though, was his work on potential theory—an alternative means of representing forces felt by an object, or fields, resulting in the mathematics of Gauss's law, the first of Maxwell's equations (describing the relationship between an electric field and the charges that create it). Gauss's other accomplishments included constructing a primitive telegraph and estimating the position of the magnetic south pole of the Earth. After his friend Wilhelm Weber was forced to leave the University of Gottingen (where Gauss himself taught), Gauss became less involved in active research, preferring to follow the developments of younger mathematicians.

Michael Faraday (1791–1867). Born the son of a blacksmith, Faraday was a self-educated bookbinder who was hired as a laboratory assistant of Humphrey Davy in 1812, with his sole recommendation being a complete set of notes on Davy's own public lectures. Faraday's humble upbringing put his early career at odds with the "gentlemen's" society of early-19th-century physics, and his treatment at the hands of Davy (who blocked Faraday's admission to the Royal Society for six years) and others almost caused him to leave science altogether.

Having learned physics with no formal training in mathematics, Faraday's work was a model of tremendous mathematical intuition and incisive analogy, with relatively little formal mathematical development. This methodology put him at odds with the likes of Ampère and Maxwell, whose work focused on careful mathematical deliberation. Across a scientific career that spanned 40 years, Faraday is most well known for his development of the concept of the electromagnetic *field*, an intermediary in the interaction of two objects at a distance.

His work in the 1830s is one of the first conclusive discoveries of electromagnetic induction—the use of changing electric and magnetic fields to create currents—which he then harnessed to build the first dynamo, a device that converts mechanical energy into electrical current and vice versa and serves as the basis for modern electrical generators. Faraday is also credited with discovering the first connections between magnetism and light, which opened the way for Maxwell's later (and most important) work.

James Clerk Maxwell (1831–1879). A Scotsman, born without privilege or high social rank, Maxwell worked in the fields of mathematical physics and electricity and magnetism during the 1800s, when the scientific community was tackling this "exotic" subject with great vigor. Maxwell was especially intrigued by the discoveries of Michael Faraday (himself a man of humble beginnings), who had introduced the concept of force field as a physically relevant entity. Maxwell succeeded in mathematically describing *all* phenomena of electric and magnetic origin in a set of four relatively simple equations, now called *Maxwell's equations*. For the most part, these equations had been developed over the previous decades by others, but Maxwell organized and formalized them and added a key component, based not on experiment but his own aesthetic mathematical sense of symmetry, intimately and permanently unifying electricity and magnetism. Maxwell discovered that these equations lead to the phenomenon of "traveling electromagnetic radiation," moving at the speed of light, and with this, he realized the deep connection of electricity and magnetism to optics, as well.

Today, Maxwell's equations and the corresponding unification of forces are regarded as one of the grand highlights of human intellectual achievement. They form the basis of electrical engineering and modern optics and have survived the discoveries of modern physics in the 20th century essentially unscathed. They paved the way for the discovery of relativity (being fully relativistic equations, even though Maxwell hadn't appreciated that!) and form the classical underpinnings of quantum electrodynamics, the quantum theory of light. Studying Maxwell's ideas generally forms the second half of any standard college-level introductory physics course.

Heinrich Hertz (1857–1894). Hertz studied under some of the finest minds in German universities and obtained his Ph.D. in physics by 1880, at the age of 23. He experimentally demonstrated the existence of electromagnetic waves, as predicted by Maxwell's equations. He also discovered the photoelectric effect, though it would take Einstein to explain its origin. Hertz died at the age of 37 (of blood poisoning). Marconi followed up quickly on Hertz's experiments as a means to send signals, with the invention of the radio.

William Thomson, Lord Kelvin (1824–1907). William Thomson is, in many ways, the bridge between Faraday's intuitive brilliance and Maxwell's ultimate formulation of electrodynamics. Raised by his father, a widowed professor of mathematics, William was precocious in his scientific exploits. By the age of 15, he had already won a prize for an "Essay on the Figure of the Earth," and he began publishing papers (under a pseudonym) by age 16. By the time he was 22, he had earned a position as the chair of natural philosophy at the University of Glasgow, a position he held for 53 years. In 1845, Thomson began corresponding with Faraday, and the two men established a relationship of mutual respect. What Faraday approached intuitively, Thomson approached with mathematical models, including the mathematics developed by his lifelong friend George Stokes in studying heat flow.

Thomson's correspondence with James Maxwell led to the latter's tackling the problem of mathematically expressing Faraday's "lines of force," an effort that culminated in what we now call Maxwell's equations.

Bibliography

Essential Reading:

Hewitt, Paul. *Conceptual Physics.* Reading, MA: Addison Wesley, 2005. This is a textbook for a course perhaps a little more technically oriented than ours, but it's really wonderful. Hewitt is very accessible, with a strong focus on sense-making and understanding. Highly recommended to go along with this course if you want to push a little farther. Be aware: Trying to "read" a textbook like this one is a difficult task. You can't read it like a work of literature (much less like the daily paper or a novel)—it requires time for calculations, projects, and reflection.

Hobson, Art. *Physics: Concepts and Connections.* Englewood Cliffs, NJ: Prentice Hall, 2003.This is a textbook for a traditional course very much like ours. Aimed at the nonscientist (no algebra, minimal use of graphs and numbers), it's a good survey of the field. Hobson follows four themes: how we know science, post-Newtonian physics (which is not an emphasis of this course!), energy, and the social context of physics. Hobson also follows a quasi-historical path, with quite a bit of discussion about the nature of science and the context and significance of the big ideas in physics.

March, Robert H. *Physics for Poets*. New York: McGraw-Hill, 1996. This book is very much on the level and style of our course. This one is not a conventional physics text at all; it has a few equations but doesn't fuss with their manipulation. It is much more a historical overview of the big ideas and central characters of physics. A good companion to this course, although a bit brief if you become interested in any given individual and, indeed, a little superficial (focusing on the "ideal physicists" rather than troubling itself with historical complexities) if you have a historical bent, but a good start for getting into this material.

Pollock, Steven, and Ephraim Fischbach, *Thinkwell Physics I* (www.thinkwell.com). This is a multimedia video textbook, a collection of 10-minute "mini-lectures" by yours truly, covering much of classical mechanics, plus waves and oscillations. These lectures are designed to go along with a much more traditional physics course, but if you concentrate on the introductory lectures in each topic (rather than on the ones focused on calculating and problem-solving), they should complement the material in this course nicely. And if you decide you do want to delve a little farther into the mathematics on your own, *Thinkwell* will certainly be a useful guide.

Recommended Reading (referenced explicitly in this course):

Crease, Robert. *The Prism and the Pendulum.* New York: Random House, 2003. A lovely book, aimed very much at the audience for this course. His theme is that science and scientific experiments can be beautiful—not in some abstract way, not stretching the definition of the word, but meaning precisely what we always mean by *beauty*. Science and scientific experiments convey harmony, symmetry, and depth; they lead us to realizations about ourselves and the world; they change our outlook in positive ways; and they make us happy. Crease has picked 10 great experiments and explains them clearly and compellingly. Although the last few reach the realm of modern physics, this book is a nice complement to this course.

Cropper, William. *Great Physicists: The Life and Times of Leading Physicists from Galileo to Hawking.* New York: Oxford University Press, 2001. Short chapters on about 30 of the most influential physicists from Galileo to Hawking, with details on both the people and the physics they discovered. There are some equations, though the math is not a heavy emphasis, and they are often treated separately from the conceptual and historical discussions. Brief by its nature but well written and a nice mix of culture, significance, and physics itself. I learned a lot from this book!

Feynman, Richard P., Robert B. Leighton, and Matthew Sands. *The Feynman Lectures on Physics*. Reading, MA: Addison Wesley, 2005. I have to include this textbook, although "reading" it is essentially an impossible task for someone not already familiar with the basics of physics. Feynman sat down with the goal of presenting the great fundamental ideas of physics at an introductory college level; the result is this compilation of notes/text for his extraordinary freshman physics course at CalTech in the 1960s. He reformulated the traditional "canon" based on his own ingenious insights, creativity, and novel point of view. Once you've got some solid understanding of the basics of physics (even somewhat beyond where this course will take you), going back to this text will be a pleasure and a reward.

Gleick, James. *Isaac Newton.* New York: Vintage Books, 2004. An engaging biography of Newton that discusses the physics only qualitatively but sets a clear background of the context and culture in which Newton worked and the significance of his work. Detailed and full of insight into Newton's personality, this book paints a more complete picture than most biographies.

Gonick, Larry, and Art Huffman. *The Cartoon Guide to Physics*. London: Collins, 2005. I know that these *Cartoon Guides* may look superficial, but I'm a fan of this series. The coverage is solid, and the books are clever and fun to read. This book matches well with our course, and there's a nice mix of representations—I believe the cartoons do help make sense of the basic ideas of classical physics.

Lightman, Alan. *Great Ideas in Physics.* New York: McGraw-Hill, 2000. Lightman zooms in on only four "great ideas" (two from classical physics, energy conservation and the second law of thermodynamics). His perspective melds physics, philosophy, and art, although he focuses on the physics, walking you through a little bit of the mathematics to get a taste for the role of math in understanding. A little limited in scope, but useful if you would like to begin the trip from conceptual physics to mathematical physics without taxing your math skills (you need to be comfortable with ratios and basic algebra). The questions for reflection at the end of the book are particularly good.

Further Recommended Reading:

Asimov, Isaac. *The History of Physics*. New York: Walker & Co., 1984. Asimov has produced a readable, comprehensive history of physics, although it's not so much history as it is details and concepts mixed in with history, biography, and philosophy of science.

Christianson, Gale. *Isaac Newton* (Lives and Legacies Series). New York: Oxford University Press, 2005. A brief, simple introduction to Newton and his physics. Although it's a little less nuanced than Gleick's biography (listed above), I nevertheless enjoyed this selection.

Cohen, I. Bernard. *The Birth of a New Physics*, rev. ed. New York: W.W. Norton, 1991. Good historical coverage of the physics of the early scientific revolution, particularly in the 16th and 17th centuries.

de Campos Valadares, E. *Physics, Fun, and Beyond: Electrifying Projects and Inventions from Recycled and Low-Cost Materials*. Englewood Cliffs, NJ: Prentice Hall, 2006. This is a collection of simple, "at-home" experiments and projects, spanning much of classical experimental physics, suitable for science fair ideas, family projects and gifts, teaching/outreach, or just plain interesting hobby activities. Great for those who prefer to learn by doing, although the author also takes care to explain the physics behind each of the projects.

Ehrlich, Robert. *Turning the World Inside Out and 174 Other Simple Physics Demonstrations*. Princeton, NJ: Princeton University Press, 1990. Another collection of physics activities and demonstrations, this one is aimed a little more at a teacher, but it provides inspiring ideas for anyone interested in watching physics in action in clear, simplified ways. Each project has detailed construction instructions and physics explanations, and almost all the projects are quite simple, requiring relatively little in the way of expense or equipment.

Epstein, Lewis. *Thinking Physics: Understandable Practical Reality*. San Francisco: Insight Press, 2002. A wonderful collection of cartoon-based "thinker" puzzles, designed to see if you have a strong conceptual understanding of many of the topics of classical physics, such as how tides work or why steel ships float. These questions are often designed at the level of an introductory college course (some of them involve sense-making of the mathematics in a traditional physics class), but by and large, there is no calculation of any kind required for these questions, just clear thinking about the underlying principles of physics. Epstein is great at talking through the wrong answers to help you "think about your own thinking."

Ferguson, Kitty. *Tycho and Kepler: The Unlikely Partnership That Forever Changed Our Understanding of the Heavens*. New York: Walker & Co., 2002. A good biography of these two remarkable historical figures that includes some of the essential physical ideas, highlighting the brilliance of Kepler's achievements.

Feynman, Richard. *The Pleasure of Finding Things Out*. New York: Basic Books, 2005.

———. *Six Easy Pieces: Essential Physics Explained by Its Most Brilliant Teacher*. New York: Basic Books, 2005.

———. *The Character of Physics Law*. New York: Modern Library, 1994.

———. *The Meaning of It All*. New York: Basic Books, 1998.

Richard Feynman is one of the great 20th-century physicists, and his perspectives on the nature of science are unparalleled. *The Pleasure of Finding Things Out* is a collection of Feynman's essays on a number of topics, offering nontechnical but delightful insights into how science is done. *Six Easy Pieces* is a collection of the least technical chapters from the *Feynman Lectures*, in which he introduces big topics of (mostly, with one or two exceptions) classical physics ideas. *The Character of Physical Law* is in a similar style, focusing on some central topics of physics and talking both about the details and the "meta" issues, the nature and consequences of science. *The Meaning of It All* drifts farther from the physics and into issues of the connections among science, religion, and

politics. There are many other books by (and about) Feynman, all of which are highly recommended, although some go beyond the "classical" focus of our course.

Gamow, George. *The Great Physicists, from Galileo to Einstein*. New York: Dover Publications, 1988. George Gamow, inventor of the Big Bang theory, is a skilled author for non-physicists. Gamow's books are gems, inspiring, and suitable even for young adults. This "biography" of physics covers much of the classical physics topics we've focused on, ending with some discussion of modern ideas.

Gribbin, John. *The Scientists: A History of Science Told through the Lives of Its Greatest Inventors*. New York: Random House, 2004. Five hundred years of science in 672 pages—this is a comprehensive book, written compellingly, with anecdotes and stories. Gribbin organizes and connects the characters and developments. A reference (you can wander from spot to spot in the book if you want) that also makes for a compelling read, albeit a little heavy going.

Heilbron, John L. *The Oxford Guide to the History of Physics and Astronomy*. New York: Oxford University Press, 2005. An encyclopedic collection (quite literally) of information about the personalities and the physics; very complete, informative, and surprisingly interesting just to read.

Holton, Gerald, and Stephen Brush. *Physics, the Human Adventure: From Copernicus to Einstein and Beyond*. New Brunswick, NJ: Rutgers University Press, 2001. Teaching physics with an accurate historical and philosophical perspective, with more history than March's *Physics for Poets*.

Jargodzki, C., and F. Potter. *Mad About Physics: Braintwisters, Paradoxes, and Curiosities*. New York: Wiley, 2001. Another collection of physics puzzles; maybe just a little less "physics-serious" than Walker's *Flying Circus* (see below), it provides briefer explanations to a broader assortment of puzzles. This entertaining book takes advantage of paradoxes as a teaching tool and includes wonderful quotes.

Jungnickel, Christa, and Russell McCormmach. *Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein*, 2 vols. Chicago: University of Chicago Press, 1990. This book focuses on the emergence of theoretical physics as a discipline, mostly in Germany and Austria, between 1850 and 1925, offering a largely biographical development and context. A scholarly work; again, a little heavy going but particularly appropriate for the electricity and magnetism section of this course.

Kakalos, James. *The Physics of Superheroes*. New York: Gotham, 2005. I may have a soft spot for whimsical physical texts, but this one strikes me as very successful at teaching the basic principles of classical physics in the context of comic-book superheroes. The comics provide a framing for Kakalos to teach the basic principles of physics in an engaging way.

Kuhn, Thomas. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press, 1996. Kuhn is a philosopher of science who popularized the notion of paradigm shifts. This book discusses the nature of the evolution and progress of scientific ideas. Kuhn argues that, for the most part, scientific progress is incremental and exists within a scientific (and sociological) framework; only rarely are "revolutions" possible. Some traditional physicists disagree with Kuhn's arguments regarding the extent to which scientific progress is socially constructed, but the work is interesting, challenging, and influential.

MacAulay, David. *The New Way Things Work*. Boston, MA: Houghton Mifflin, 1998. A cartoon-based book, whimsical and amusing, it takes an engineering and physics approach to examine devices and ask how they work, incorporating physics concepts in a meaningful way. Aimed at children, but child-like adults (like me) can appreciate this book.

Mahon, Basil. *The Man Who Changed Everything: The Life of James Clerk Maxwell*. New York: John Wiley & Sons, 2004. A brief and readable biography of Maxwell's life and science. It doesn't get so much into the physics but offers good insights into Maxwell as a human being and scientist!

Nye, Mary Jo. *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*. Cambridge, MA: Harvard University Press, 1999. A thorough study of the two sciences together, emphasizing the social and historical context.

Purrington, R. D. *Physics in the Nineteenth Century*. New Brunswick, NJ: Rutgers University Press, 1997. A little heavy going, this is pure historical analysis but covers all the major players in the physics of the 1800s, with an emphasis on the development of ideas leading to the coming revolutions of the 20th century.

Shamos, Morris, ed. *Great Experiments in Physics: Firsthand Accounts from Galileo to Einstein*. New York: Dover Publications, 1987. A collection of 25 key experiments (including many discussed in this course), introduced and

explained, then followed with annotated original works. A unique book; it's great (and surprisingly rare) to read the originals.

Spielberg, N., and B. Anderson. *Seven Ideas That Shook the Universe*. New York: Wiley, 1995. A comprehensive text, covering the ideas of this course and following a conceptual framework. Aimed at the non-physicist. A highly readable text.

Vollmann, William. *Uncentering the Earth: Copernicus and the Revolutions of the Heavenly Spheres*. New York: W.W. Norton, 2006. A book (written by a nonscientist) that explores how Copernicus could have come up with the heliocentric hypothesis and convinced himself of its correctness. Not always the easiest read but a fascinating story that gets at the core of the start of the scientific revolution and the nature of scientific reasoning.

Von Baeyer, Hans Christian. *Warmth Disperses and Time Passes: The History of Heat*. New York: Modern Library, 1999. A well-written historical and physical treatment of thermodynamics. A good introduction to the story of thermodynamics, which alas, we barely have time to even introduce in this course.

Walker, Jearl. *The Flying Circus of Physics with Answers*. New York: Wiley, 1977. A collection of "puzzles," all curious, real-world phenomena for you to think about, that demand physical explanation: Why does chalk squeak? How does a one-way mirror work? What's the "green flash" at sunset? Why wasn't Ben Franklin killed when he flew his kite in a lightning storm? These questions are a lot of fun to explore! The puzzles are organized around broad themes of classical physics (such as mechanics, optics, acoustics, thermodynamics, and so on).

Standard Introductory Physics Textbooks (a selection):

A number of textbooks are used in introductory college-level physics courses. These are not generally designed as "standalone" reading but are meant to be used with the guidance and support of an instructor. If you decide to buy one to try out on your own, be advised that these are not "evening reading material." There are so many, I list below only a few of my personal favorites (the one I authored, *Thinkwell Physics*, was listed with the essential texts, above). Many others are in use in college courses around the world; this is a very abbreviated list!

Bloomfield, Louis. *How Things Work: The Physics of Everyday Life*. New York: Wiley, 2005. An unconventional introduction to physics, aimed at nonscientists who want to learn the basic principles of physics and the applications to everyday life. Rather than organizing the text around physics concepts, the author focuses each chapter on a technological or physical application (generally both common and interesting!). This approach develops the physical principles in a deeply motivating way. Of all the texts listed in this section, Bloomfield's is likely to be the most accessible to the interested layperson, but even so, it remains a textbook that would probably best be used in the framework of a course with an instructor.

Chabay, Ruth, and Bruce Sherwood. *Matter and Interactions*. New York: Wiley, 2003. Most of the standard introductory texts follow pretty much the same pattern, teaching the same classical physics topics in roughly the same order (perhaps adding modern physics in the end) and focusing on the same mathematical skills. This text offers a fresh approach. Sherwood and Chabay are part of the physics education research community and treat introductory physics from a completely modern perspective. Relativity and the atomic model are involved right from the start, and the separation between classical and modern physics is purposefully blurred. The authors emphasize modeling systems throughout. If you want to learn physics with the intent of becoming a physicist, this would be an excellent first textbook to use, but again, the level of mathematics and sophistication required is fairly high; this is certainly not "light reading."

Giancoli, Douglas. *Principles with Applications*. Englewood Cliffs, NJ: Prentice Hall, 2004. This is a fairly traditional and popular introductory textbook, designed specifically for an algebra-based course. Many of the applications and examples in the book are tailored to students who are less likely to be physicists or engineers but might be interested in medicine, biology, or architecture.

Halliday, David, Robert Resnick, and Jearl Walker, *Fundamentals of Physics* (New York: Wiley, 2004), or perhaps, Karen Cummings, Priscilla Laws, Edward Redish, and Patrick Cooney, *Understanding Physics* (New York: Wiley, 2004). Halliday, et al., has been one of the standard texts at many schools for many years. As you move up to more recent editions, there is a stronger focus on conceptual understanding. The *Understanding Physics* book is basically a new, updated version, redesigned to incorporate physics education research results, but it is nevertheless still a dense, heavy, mathematically centered introductory text. It remains one of my favorites for teaching calculus-based physics and engineering courses.

Knight, Randall. *Physics for Scientists and Engineers: A Strategic Approach*. Reading, MA: Pearson/Addison-Wesley, 2003. Similar in content to Halliday, Resnick, and Walker, above. Knight has also taken a stab at rewriting

the conventional introductory calculus-based textbook with physics education research results in mind. That means using research on common student learning difficulties, incorporating alternative representations and metaphors, and including problems and questions designed through iterative research studies.

Moore, Thomas. *Six Ideas That Shaped Physics*. New York: McGraw-Hill, 2003. This is another modern, nonstandard approach to the introductory text. Breaking the subject into six fundamental "big ideas" (such as conservation laws, reference frame–independence of physics, universal laws, and so on), Moore leads the student to apply basic principles to solve realistic physical problems, rather than following a more traditional, plug-'n-chug, formula-centric approach.

Internet Resources:

The Web has an overwhelming supply of resources regarding introductory physics (*some* of which are even accurate and useful)! The task of selecting just a few sites is difficult (and the situation will likely evolve so quickly as to limit the usefulness of this list), but below are a few Web sites that I believe are definitely worth investigating.

http://phet.colorado.edu. This is the simulation site referred to throughout this course, developed by the Physics Education Research group at the University of Colorado.

http://natsim.net/en.html. This site contains links to other physics simulation collections. Although the phet sims (listed above) are very helpful, they cover only a narrow range of topics. This page will take you to sites with hundreds of applets. In addition, you might want to visit sites mentioned explicitly in the lecture notes:

- www.cecm.sfu.ca/~scharein/astro
- www.walter-fendt.de/ph11e
- http://physics.bu.edu/~duffy/semester1

http://howthingswork.virginia.edu/. Louis Bloomfield (whose introductory textbook for nonscientists, *How Things Work*, is also on my recommended list) has created a high-quality frequently-asked-questions page for explanations about the physics of everyday life. If you have a question about a device or phenomenon, there's a pretty good chance you will be able to find an answer on this page.

http://www.merlot.org/merlot/materials.htm?category=2737. The Merlot Web site (www.merlot.org) is a national resource for academics in a variety of fields to compile learning materials. The link above takes you specifically to a collection of peer-reviewed resources for classical mechanics. (Moving up a level will allow you to explore more of physics, including electricity and magnetism and modern physics)

www.aip.org/history/syllabi/books.htm. The AIP is the American Institute of Physics. This is the institute's "bibliography" page, with many highly recommended books. (Some of them I have listed above, but I've tried to keep my bibliography distinct. AIP's selection is very good!)

www.aip.org/history/gap/. Another AIP page, this one has links to the works of some great American physicists (including original papers, with explanations), including Franklin, Gibbs, and many others.

www.physlink.com/Education/History.cfm. A collection of links to other sites, with history and timelines. Also many links to science museums.

www-gap.dcs.st-and.ac.uk/~history/index.html. This page calls itself the History of Mathematics Archives, but it's very thorough, and its compilers apparently consider most physicists to be mathematicians. The biographies are interesting and comprehensive without being overwhelming. This is my favorite site for a "quick read" about some historical figure I'm interested in.

www.upscale.utoronto.ca/PVB/PVB.html. This is the University of Toronto's *Physics Virtual Bookshelf*. The staff at the university has put together an impressive collection of links and articles. A nice place to start digging deeper into the history and content of physics.

http://en.wikipedia.org/wiki/Physics. Wikipedia is a collective, informal, Web-based encyclopedia. This site is frequently helpful, and I use it all the time (not just for physics!). But beware: It is the nature of Wikipedia that there can, on occasion, be mistakes or even sheer nonsense here. These articles are submitted by individuals without "authorization"; this is not the usual method of scientific peer review by any stretch of the imagination. If you learn something here, follow up to make sure that it's accurate and reliable. Nevertheless, Wikipedia is often my first stop when I'm looking up something new.

www.physics.org/. From the Institute of Physics, many links and interactive sites for history and the "physics of everyday life."

http://physicsweb.org/bestof/history. Another compilation of historical information and links, this one put together by the Institute of Physics (IoP).

www.hssonline.org/teach_res/essays/mf_essays.html. A recommended bibliography from the History of Science Society. Once again, many good books here, organized in a variety of categories (social, historical, bibliographic). An excellent resource for delving further into the history of classical physics!

http://galileo.rice.edu/. A comprehensive Web site about Galileo.

www.tychobrahe.com/eng_tychobrahe/index.html. A comprehensive Web site about Brahe.

www.clerkmaxwellfoundation.org/. A comprehensive Web site about Maxwell.