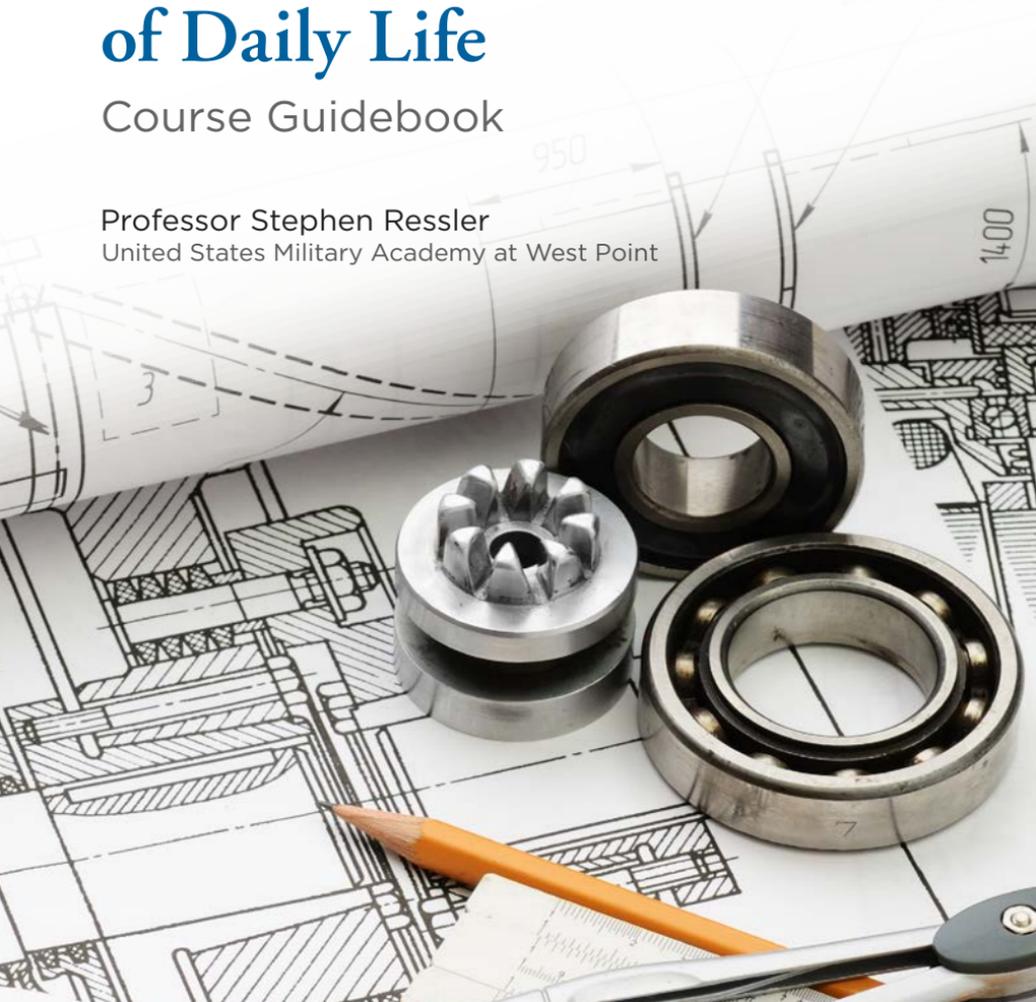


Everyday Engineering Understanding the Marvels of Daily Life

Course Guidebook

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United States Military Academy at West Point



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Dr. Ressler served for 34 years as a commissioned officer in the U.S. Army Corps of Engineers and retired at the rank of brigadier general in 2013. He served in a variety of military engineering assignments in the United States, Europe, and Central Asia, including 21 years as a member of the West Point faculty. At West Point, he taught courses in engineering mechanics, structural analysis, structural design, construction management, professional practice, and civil engineering history. In 2007, he deployed to Afghanistan to develop a civil engineering program for the newly created National Military Academy of Afghanistan in Kabul. In that capacity, he designed the civil engineering curriculum, hired the first cohort of Afghan faculty, and developed two laboratory facilities.

Dr. Ressler has focused his scholarly work and professional service in the area of engineering education. He has written more than 80 scholarly papers on teaching techniques, faculty development, curriculum assessment, engineering outreach to primary and secondary schools,

engineering accreditation, and information technology. His work has earned nine Best Paper Awards from the American Society for Engineering Education (ASEE) and one from the American Society of Civil Engineers (ASCE).

Dr. Ressler is the creator and director of the Engineering Encounters Bridge Design Contest (<https://bridgecontest.org>), a nationwide Internet-based engineering competition that has engaged more than 50,000 middle school and high school students since 2001. He is also a developer and principal instructor for the Excellence in Civil Engineering Education (ExCEEEd) Teaching Workshop, a landmark faculty development program sponsored by ASCE. The workshop has provided rigorous teacher training to more than 500 civil engineering faculty members from more than 200 colleges and universities over the past 14 years.

Dr. Ressler has won numerous national awards for engineering education and service. From ASCE, he received the President's Medal and the ExCEEEd Leadership Award. ASCE also named him a Distinguished Member in 2005. From ASEE, he received the George K. Wadlin Distinguished Service Award, the Distinguished Educator Award, and the Dow Outstanding New Faculty Award. He also received the Society of American Military Engineers' Bliss Medal for Outstanding Contributions to Engineering Education, the American Association of Engineering Societies' Norm Augustine Award for Outstanding Achievement in Engineering Communications, the Premier Award for Excellence in Engineering Education Courseware, and the EDUCOM Medal for application of information technology in education.

Dr. Ressler was named one of *Engineering News-Record's* Top 25 Newsmakers Who Served Construction in 2000. Most recently, he received ASCE's highest award—the Outstanding Projects and Leaders (OPAL) Award for 2011. The OPAL Award is presented to only five of ASCE's 140,000 members each year.

Dr. Ressler's other Great Courses are *Understanding Greek and Roman Technology: From Catapult to the Pantheon* and *Understanding the World's Greatest Structures: Science and Innovation from Antiquity to Modernity*. ■

Disclaimer

This series of lectures is intended to increase your understanding of the principles of engineering. These lectures include demonstrations in the field of engineering, performed by an experienced professional. These experiments may include dangerous materials and are conducted for informational purposes only, to enhance understanding of the material.

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Everyday Engineering

Understanding the Marvels of Daily Life

When we think about modern engineering and technology, we instinctively tend to think about sophisticated computing devices, jet aircraft, robots, and lasers. But in many ways, the products of modern engineering that have the most substantial influence on our lives are the ones we almost never think about—the everyday technologies that surround us in our homes and workplaces and the infrastructure systems that have been so beautifully integrated into the fabric of modern civilization that they are inevitably taken for granted.

The purpose of this course is to explore these everyday technologies from an engineering perspective. Consistent with this purpose, the scope of the course is limited to the major technological systems we are most likely to encounter in and around our homes and during a drive across town.

The course begins with a detailed examination of the typical American single-family residence as an engineered system consisting of eight distinct but interrelated subsystems: structure, foundation, building envelope, site, plumbing, electrical system, heating and cooling system, and telecommunications. Several of these subsystems are integrally connected to vast infrastructure networks—such as municipal water supply and sewage, the electrical power grid, and the public telephone network—and the course addresses these large-scale engineered systems as well. We also consider a few representative examples of the thousands of simple machines and gadgets that surround us within our homes.

The course then shifts gears, with an introduction to the principal technological systems used in our automobiles: the internal combustion engine and drivetrain, as well as the automotive suspension, steering, and braking systems. Armed with a better understanding of automotive engineering, we then “hit the road” for an overview of transportation engineering: roads, bridges, tunnels, and railroads. The course concludes

by considering the technological challenge of solid waste disposal, as a lead-in to an overview of sustainable engineering design.

For each of the technologies addressed in these lectures, we attempt to answer three questions.

- ▶ How does it work?
- ▶ What are the key scientific principles on which its design and operation are based?
- ▶ Because no technology is perfect, how and why does it sometimes fail?

In answering these questions, the course seeks to create informed users of technology, who are better equipped to understand, appreciate, and engage with the engineered systems that contribute so much to our modern quality of life. ■

Engineering and Technology in Your World

LECTURE

1

When we think about modern engineering and technology, we instinctively tend to think about sophisticated computing devices and consumer electronics, jet aircraft and bullet trains, and robots and lasers. But in many ways, the products of modern engineering that have the most substantial influence on our lives are the ones we almost never think about—the everyday technologies that surround us in our homes and workplaces. The purpose of this course is to explore these everyday technologies that contribute to our quality of life in such a vital, if unobtrusive, way. This exploration will be conducted from an engineering perspective, with an emphasis on how these products and systems work and on the underlying science that influenced their design and that ultimately determines how well they work.

What Is Engineering?

- ▶ **Engineering** is the application of math, science, **technology**, and experience to create a system, component, or process that serves our society.
- ▶ Science provides us with explanations about how the physical world works. Sometimes these explanations are true representations of nature—but they often aren't.
- ▶ For example, Sir Isaac Newton's laws of motion serve as a scientific basis for the design of most current everyday technologies, even though we know that these laws aren't strictly correct representations of how physical bodies move in time and space. From an engineering perspective, Newton's laws are much simpler to apply than Einstein's theory of general relativity—and for most practical applications, their predictive power is entirely sufficient for their use in the design of engineered systems.

- ▶ Indeed, from an engineering perspective, the only things that really matter about a scientific theory are its predictive power and its ease of application.
- ▶ A historical case in point is the scientific theory of **heat**. The first coherent theory describing heat as a form of energy equivalent to mechanical work was published by Sir Benjamin Thompson in 1798. By the 1850s, the principal laws of thermodynamics had been formulated and were proving quite useful in the design of steam engines. However, as late as the 1880s, scientists were still debating what heat actually is, with some claiming (incorrectly) that it's a **fluid**, which they called "caloric," and others claiming (correctly) that heat is the motion of the particles constituting matter. But even as the scientists debated, the engineers had a scientific theory that could predict the **power** output of various steam engine designs with reasonable accuracy—and that was all that mattered.
- ▶ To engineers, the predictive power of a scientific theory is so important because every engineering design is, at the most fundamental level, a prediction of the future. When an engineer designs a bridge, he or she is predicting that the **structural system** will be capable of safely carrying the maximum **load** the bridge is likely to experience over its entire lifetime. And the basis for this is a series of scientific models used to predict **internal forces**, **stresses**, deformations, and material **strengths**. None of these predictions is perfectly accurate, but all are sufficiently accurate to produce safe designs.
- ▶ All of these scientific models are expressed mathematically, because physical phenomena are inherently quantitative in nature. Mathematics is also the language of engineering, because technological systems are envisioned, designed, specified, and constructed quantitatively.
- ▶ The relationship between engineering and technology is particularly fascinating because technology is both a means to an end and the end itself. The product of engineering is technology. Yet technology is also instrumental to the modern engineering design process.



**Every engineering design is, at the most fundamental level,
a prediction of the future.**

- ▶ Virtually all modern engineering designs use information technology, because the computational demands associated with our modern scientific models can be met far more efficiently by computers than by stubby pencils and mechanical calculators. But pencils and calculators are technologies, too, and they continue to perform an important role in modern engineering—as do all sorts of other technologies, such as materials testing equipment, measuring instruments, and the machinery associated with manufacturing and construction. These tools of the engineering process are themselves all products of engineering.
- ▶ This same sort of circular relationship also exists between science and technology. Science contributes immeasurably to the design of modern technology, and modern science would be impossible without technological tools like electron microscopes, satellites, and particle accelerators.

- ▶ Its value notwithstanding, the role of science in engineering is sometimes overstated. After all, many of humankind's most important inventions and technological innovations have been created with little or no scientific basis. At best, the people who built the first wheeled vehicles, waterpower, **aqueducts**, and cathedrals could only draw from a qualitative understanding of the physical world. The invention of the steam engine preceded—and actually inspired—the science of thermodynamics.



- ▶ Conversely, the role of experience in engineering is often underappreciated. Consider the modern automobile, the invention of which is generally attributed to Karl Benz in 1886. In the years since then, the sciences of **mechanics**, thermodynamics, chemistry, and electricity have contributed mightily to the development of this machine. But much of its long-term development must also be attributed to experience—careful observation, empirical testing, trial and error, and meticulous refinement—interspersed with occasional bursts of creative insight. This side of engineering has little to do with science and everything to do with ingenuity.

Why Study Everyday Engineering?

- ▶ Why is everyday engineering a subject worth studying, even if you're not an engineer? The following are three reasons.
 - We can all benefit from being informed users of technology. For example, when your **plumbing system** breaks, you'll benefit from understanding what went wrong, even if your plumber will be doing the repair.
 - Knowing something about everyday engineering can make us all better citizens. As an engaged citizen, you should take well-reasoned positions on issues like deregulation of the power industry, public investment in transportation **infrastructure**, and the environmental impact of **shale gas** exploration—and you should consider these issues when you vote for the officials who influence these policies. You can't really take a well-reasoned position on any of these issues without some understanding of the associated technologies.
 - Perhaps most importantly, everyday engineering is immensely rewarding, and it's fun to learn more about the world around us.
- ▶ As you explore the world of everyday technology throughout this course, you will encounter the following recurring themes.

- There is no such thing as an ideal technology; engineering always involves trade-offs. To achieve an optimum solution with respect to one criterion, we must inevitably compromise on one or more other criteria.
- There is a collective love-hate relationship with technology. For example, we're addicted to our **cell phones**, but we'll vigorously protest the construction of a new cell tower in our neighborhood. This course can help reconcile these kinds of contradictory positions a bit.
- Government plays a substantial role in everyday engineering. Throughout this course, you will learn about the impacts of government regulation, but you also will learn how deregulation has reshaped various industries and has significantly influenced the services we receive from them. You will learn how government incentive programs have been used to spur technological development—sometimes for better and sometimes for worse. As you will learn, the impact of government involvement depends on the specific government action, the context, the interface with relevant professional communities, and the technology itself.
- Remarkable human achievements are reflected in the seemingly mundane works of everyday engineering. Our beautifully integrated systems for residential construction, water purification, electrical power **distribution**, telecommunications, and transportation are triumphs of human imagination, ingenuity, and persistence that substantially improve the quality of life for millions of people. As you experience these human achievements throughout this course, you hopefully will gain a keener appreciation for the work of the countless engineers who have done so much good work, largely behind the scenes, to make our lives better.

TERMS

aqueduct: A conduit used to transport water from its source to its point of use.

cell phone: A radio transmitter-receiver used in cellular communication.

distribution: (1) The movement of potable water from a local reservoir or water treatment facility to consumers. (2) The movement of electrical power from a substation to consumers.

engineering: The application of math, science, technology, and experience to create a system, component, or process that serves our society.

fluid: A liquid or gas.

heat: Thermal energy transferred from a region of higher temperature to a region of lower temperature.

infrastructure: Large-scale technological structures and systems that enhance societal functions, facilitate economic development, and enhance quality of life. The most common infrastructure systems are electrical power, water supply, wastewater disposal, storm drainage, solid waste disposal, transportation, and telecommunications.

internal force: A force developed within a structural element in response to one or more applied loads. An internal force can be either tension or compression.

load: A force applied to a structure. Types of loads include dead load, live load, snow load, wind load, and seismic load.

mechanics: A branch of science that deals with the effects of forces acting on physical bodies.

plumbing system: A building subsystem that provides clean water to fixtures and transmits wastewater outside the building for disposal.

power: (1) The rate at which work is done, measured in units of force \times distance \div time. (2) Voltage \times current, measured in watts (or volt-amps).

shale gas: Natural gas that is found within and extracted from shale, usually through the process of hydraulic fracturing.

strength: The maximum force a structural element can carry before it fails. Strength can be defined for both tension and compression.

stress: The intensity of internal force within a structural element, defined in terms of force per area (e.g., pounds per square inch).

structural system: An assemblage of structural elements—e.g., beams, columns, rafters, trusses, wall panels, and connections—designed to carry load safely.

technology: The product of engineering.

READING

Kosky, Balmer, Keat, and Wise, *Exploring Engineering*.

QUESTIONS

- 1 In the room where you are currently located, how many different pieces of everyday technology can you identify?
- 2 The product of engineering is a system, component, or process that serves society. Can you think of a common process that was designed by an engineer?

Your House as an Engineered System

In this lecture, we'll begin our exploration of everyday engineering by focusing our attention on one particularly important technological system that, quite literally, surrounds us in our daily lives. For the next four lectures, you will examine your house—first as an engineered system in its own right and then in its broader technological context—as one component of the extraordinary system of systems comprising our civil infrastructure. In this lecture, you also will be introduced to the rather unlikely hero of this story: the regulatory document that governs the safety, economy, constructability, and efficiency of residential construction throughout the United States, the building code.

Your House

- ▶ A well-designed, well-built, and well-maintained house provides a rather impressive array of technological functions. These functions are fulfilled by an integrated assemblage of eight major building subsystems, the design of which implies a high level of engineering sophistication.
 - The structural system supports the weight of the building itself, the weight of snow and ice on the roof, the occasionally severe environmental loads caused by wind and possibly earthquakes, and the weight of people and their accumulated stuff.
 - The **building envelope** is a highly specialized set of building components that keeps the elements out and helps maintain an appropriate range of temperature and humidity inside, while also allowing for access, egress, and natural illumination.
 - The **foundation** is, in one sense, a part of the structural system—because it transmits the weight of the building and other loads safely down into the earth. But it also serves as a critically important

component of the building envelope: protecting the home from **groundwater** infiltration and heat loss and sometimes enclosing additional living or utility space.

- The heating, ventilating, and air-conditioning (**HVAC**) system provides control of temperature and humidity while also supplying fresh air.
- The **electrical system** provides electrical power to outlets, light fixtures, appliances, air-conditioning, perhaps heating, and various control systems (such as the **thermostats** that control both your HVAC system and your hot-water heater).
- The plumbing system delivers fresh water under pressure to various **fixtures** throughout the building and removes **wastewater** from these same fixtures.



sewage assembly

- The telecommunications system includes phone, cable, and wireless links that enable the **transmission** of information to and from the outside world.
- Your building site, the plot of land on which your home is situated, provides structural support for your foundation, controls the flow of storm water across the site, and connects your residence to the local road network (via your driveway) and to public utilities (via curbside connections).
- ▶ From a macro perspective, these subsystems are highly integrated components of a much bigger whole. These building subsystems are integrated within three different aspects of residential design and construction.
 - Those eight subsystems must be integrated with each other. They are highly interdependent. For example, your water supply lines, wastewater pipes, electrical wires, telecommunication cables, and air-conditioning ducts must all pass through structural wall framing and floor framing without adversely affecting their load-carrying capacity.
 - The eight subsystems must work within the context of a broader architectural design. Typical elements of architectural design for a residential building include the allocation of interior space to various rooms and functions (defining how large each room should be); access and circulation (defining how occupants will enter, exit, and move around within the home); **adjacencies** (defining which rooms should be close together and which should be far apart); **fenestration** (defining the sizes and locations of windows); the locations of major appliances and fixtures; and aesthetics, which includes the house's overall style and form, position on the building site, and exterior and interior materials, finishes, and details.
 - The subsystems must be integrated within large-scale civil infrastructure systems. Unless you're living in a log cabin in the wilderness, your house is embedded within a large, complex



Architects must account for space allocation, access and circulation, adjacencies, fenestration, aesthetics, and building codes.

network of civil infrastructure. (The term “infrastructure” refers to large-scale technological structures and systems that enhance societal functions, facilitate economic development, and enhance quality of life.) The most important elements of civil infrastructure are transportation, electrical power, water supply, wastewater disposal, storm-water management, and telecommunications.

Building Codes

- ▶ A **building code** is a set of rules specifying minimum standards for construction. Its principal purpose is to protect public health, safety, and welfare—though modern codes also promote such secondary concerns as economy, constructability, and sustainability.

- ▶ Historians attribute the invention of the building code to King Hammurabi of ancient Babylon. Indeed, the Code of Hammurabi in the 18th century B.C. includes a series of provisions like this one: “If a builder builds a house for someone, and does not construct it properly, and the house which he built falls in and kills its owner, then that builder shall be put to death.” That’s a pretty good incentive for construction quality, but it doesn’t do much to inform the builder about how he or she might avoid a structural collapse.
- ▶ Modern codes have adopted a significantly more prescriptive approach, by adopting technical standards aimed at preventing particular types of failure from happening. Not surprisingly, these initiatives to expand the scope and technical demands of building codes typically followed large-scale disasters, such as the Great Fire of London in 1666, the Chicago fire of 1871, the San Francisco earthquake of 1906, and Hurricane Andrew in 1992.
- ▶ The 20th century saw important trends in the development of building codes. As engineering knowledge expanded at an ever-increasing rate, the associated codes became ever larger, ever more complex, and ever more prescriptive. With each new building failure or new research finding, code provisions were added to address the underlying issue. At the same time, building codes became increasingly Balkanized, with wide variations in standards across regions, cities, and municipalities.
- ▶ In part to address these problems, responsibility for code writing in the United States gradually passed from governments to nonprofit professional societies, called **standards organizations**, which could claim national or international scope while also commanding the high-level technical expertise necessary to develop codes reflecting current best practices.
- ▶ Because these standards organizations had (and still have) no legislative authority, they instituted the system of **model codes** that remains in use today. A model code is, in essence, the consensus recommendation of the professional community represented by a particular standards organization.

- ▶ Although the development of model codes was beneficial, U.S. building codes were still a mess until late in the 20th century. At that time, three major standards organizations were promulgating three independent model codes, and adoption of these codes across the country was haphazard at best. But that situation changed dramatically in 1994, when these three organizations merged to form the International Code Council (ICC). By 2000, the ICC was publishing the first true national building codes in the United States.
- ▶ The ICC is a professional society composed of technical experts, industry representatives, and regulators who work collaboratively to develop 15 interrelated and complementary model codes, including the International Building Code, the International Energy Conservation Code, and the International Residential Code.
- ▶ ICC codes are developed and updated through a structured and highly participatory process implemented on a regular three-year cycle. Anyone in the world can submit a proposed code change, and hundreds are considered during every three-year change cycle.
- ▶ Over time, as model codes have become increasingly standardized, more governmental jurisdictions have been willing to adopt them through legislation. Code writing is a complicated business, requiring considerable time and technical expertise, so it makes sense to hand off this process to the professionals. Moreover, widespread adoption of standardized model codes is highly advantageous to builders and developers who work in multiple political jurisdictions.
- ▶ Residential construction directly affects a huge proportion of our population, and there's strong popular desire to keep housing costs as low as possible. As a result, over the past century, the model building codes have standardized and institutionalized residential construction methods at such a high level of detail that the codes can effectively serve as a substitute for an engineer's design.

- ▶ Building codes enhance public safety by ensuring that builders use appropriate materials and methods, reduce overall construction costs by eliminating the need to hire professional engineers to design standard buildings, provide a mechanism for managing ever-increasing complexity in the construction industry, and provide a means of motivating builders toward long-term societal goals (such as greater sustainability) that they might not pursue otherwise.
- ▶ But building codes also limit builders' flexibility, inhibit innovation, and create incentives for the proliferation of bland, look-alike homes; increase construction costs through excessively prescriptive requirements, many of which are unrelated to public safety; and tend to foster a bureaucratic emphasis on compliance, rather than reliance on the professional judgment of designers and builders.
- ▶ Building codes are a fact of life in our modern technology-intensive world, and in myriad ways, they determine the character of your home—its design as an engineered system and its integration with the civil infrastructure that surrounds us. So, it's in our best interest to understand what they are and how they work.

TERMS

adjacency: An aspect of an architectural design dealing with the proximity of rooms and other functional spaces to each other.

building code: A set of rules specifying minimum standards for construction. Building codes are normally enacted through legislation.

building envelope: An assemblage of building components that protect interior spaces from the elements and control interior temperature and humidity, while also allowing for access, egress, and natural illumination.

electrical system: A building subsystem that provides electrical power to outlets, light fixtures, appliances, control systems, and other devices.

fixture: In a plumbing system, a device that draws clean water from the water distribution system and discharges wastewater into the sewage system without allowing any flow in the opposite direction.

fenestration: The sizes, locations, and types of windows in an architectural design.

foundation: An assemblage of building elements that transmit loads from the structural system into the Earth.

groundwater: Water that percolates down through the soil and accumulates in an underground aquifer.

HVAC: The heating, ventilating, and air-conditioning system for a building.

model code: A set of technical standards, guidelines, or specifications promulgated by a professional standards organization but having no legal status or enforcement mechanisms. When a model code is adopted by a government entity through legislation, it becomes a building code.

standards organization: A nonprofit professional society that formulates one or more model codes.

thermostat: A mechanical or electronic device used to control temperature.

transmission: (1) The movement of electrical power over long distances from power-generating facilities to the regions in which the power will be consumed. A transmission line terminates at a substation. (2) In an automobile drivetrain, a device that keeps the engine rotating within its most efficient range of operation while providing adequate torque across the full range of vehicle speeds.

wastewater: All liquid and solid material that drains from plumbing fixtures in a building or other facility.

READINGS

Hayes, *Infrastructure*.

International Code Council, *2015 International Residential Code*.

Wing, *The Visual Handbook of Building and Remodeling*.

QUESTIONS

- 1** In what ways are your home's electrical system, plumbing system, and building envelope interdependent?
- 2** Of the eight building subsystems, which ones would be easiest to modify or replace in an existing home? Which ones would be most difficult to modify or replace?

Three Structural Systems for Load Bearing

From an architectural perspective, a private home is a mirror, reflecting the aesthetic preferences and lifestyles of the society, the community, and the era in which that home was built. Given the diversity of individual tastes and never-ending changes in architectural fashion, it's hardly surprising that residential construction comes in such a seemingly limitless variety of shapes and sizes. However, if we could peer beneath the architectural skin of various homes, we would find a surprising degree of consistency in structure. In this lecture, you will learn about the three residential structural systems: light wood frame, bearing wall, and heavy timber frame.

Structural Systems and Loads

- ▶ Most homes use essentially the same structural system—a configuration called **light wood frame construction**. The light wood frame is one of only three principal types of residential structural systems that have been used throughout recorded history and across much of the civilized world. The other two—**bearing wall construction** and **heavy timber frame construction**—are traditional forms that have been around for millennia. Light wood frame construction wasn't invented until the mid-19th century, but it has dominated residential construction in North America since then.
- ▶ A structural system is an assembly of structural elements that work together as an integrated whole to carry such diverse loads as the weight of snow on your roof, a tub full of water in your bathroom, the china cabinet in your dining room, a crowd of people attending your cocktail party, a gale-force wind, and the weight of the house itself.



light wood frame construction

- ▶ A load is a **force**—a push or a pull—that’s applied to a structure. The concept is simple, but the process of determining the magnitudes, directions, and configurations of loads for the purpose of structural design can be complex. Fortunately, this process is greatly facilitated by building codes. The International Residential Code identifies five principal categories of load that are most relevant to our understanding of residential construction.
 - Dead load is the weight of the building itself, including structural elements (such as **beams** and **columns**), nonstructural components (such as shingles and windows), and permanent fixtures (such as bathtubs and kitchen cabinets). Dead loads are fixed in both position and magnitude, and they’re usually associated with known quantities of physical stuff, so their magnitudes can be determined quite accurately without a lot of detailed guidance from the code.

- **Live load** consists of the weight of people and all of their movable stuff, such as furniture, books, and housewares. Live loads are highly variable in both magnitude and position, and they can change dramatically over time. Given this inherent unpredictability, we need to rely heavily on the institutionalized wisdom of the building code to help us estimate these loads. Live load is specified as a pressure, measured in pounds per square foot.
- Snow load, like live load, is specified in pounds per square foot. But unlike live load, snow load is applied to the roof of the structure, and its magnitude varies according to the building's geographic location and roof configuration. The code provides all of the necessary adjustment factors to account for variations.
- Wind load is caused by moving air striking and then moving over and around a building. According to fluid mechanics—a branch of physics dealing with liquids and gases—the air pressure above and behind a building is lower than the pressure inside the building, and this pressure difference forces the roof and the downwind wall outward. The two net effects of these pressure loadings are a substantial horizontal force and a net uplift force, both of which can significantly influence the structural design.
- Seismic load is caused by earthquakes, which cause the ground beneath a structure to accelerate horizontally. This motion causes the structure to oscillate rapidly back and forth. With each oscillation, the lateral acceleration of the building's mass is mathematically equivalent to a large horizontal force pushing the structure sideways. For residential construction in all but the most earthquake-prone regions, the structural elements that resist horizontal wind force are the same ones that resist the equivalent horizontal seismic force.
- ▶ Dead, live, and snow loads are often grouped together as **gravity loads**, which are called this because they're all associated with the weight of something—building materials, people, furniture, snow—and thus are always oriented vertically downward. Wind and seismic load are fundamentally different, in that they're not associated with gravity and

are applied primarily in a horizontal direction. For this reason, wind and seismic loads are often called lateral loads.

How Structures Respond to Loads

- ▶ When external loads are applied to a structural system, they cause internal forces, which are transmitted through the individual elements comprised by that system. A structural element will respond to these internal forces in any of four ways, depending on the configuration of the element within the structural system:
 - If the element is stretched, it elongates and is said to be in **tension**.
 - If the element is squashed, it shortens and is said to be in **compression**.
 - If the element is loaded transversely, it bends. Bending is a combination of both tension and compression.
 - If the ends of an element are rotated in opposite directions, the element twists and is said to be experiencing **torsion**.
- ▶ A structural element with a particular set of dimensions, made of a particular material, has a well-defined strength with respect to each of these four behaviors. For example, tensile strength is the maximum tension force that an element can carry before it ruptures.
- ▶ Tensile strength, compressive strength, bending strength, and torsional strength can be determined experimentally through laboratory testing; however, more usefully, they can be predicted with a fairly high degree of accuracy using a variety of different scientific and computational tools. These analysis tools are fundamental to the structural design process.
- ▶ The principal objective of structural design is to ensure that, for all relevant types of loading, the predicted strength of each element in the structural system is adequate to carry the associated internal forces safely.

Residential Structural Systems

- ▶ Primitive forms of bearing wall construction can be traced back to distant antiquity. Indeed, one of the world's earliest known cities—Çatalhüyük, located in modern-day Turkey—was composed entirely of domestic buildings with mud-brick bearing walls surmounted by timber roofs. In the United States, bearing wall buildings dominated residential construction throughout the colonial era and well into the 19th century.
- ▶ In a bearing wall structural system, the principal vertical load-carrying elements are the building's exterior walls, which are typically made of solid stone, solid brick, mud brick or adobe, or solid wood. The exterior walls are supported on a stone or **concrete** foundation—called a wall **footing**, because it extends along the full length of the load-bearing wall. Usually, interior floors and roofs are supported on **joists** set into notches. When a gravity load is applied, joists carry the load in bending and transmit the load out to perimeter walls, which transmit in compression through footings to the soil.



Çatalhüyük, in modern-day Turkey

- ▶ The traditional bearing wall structural system is relatively more expensive than the other two types, because those solid exterior walls generally require a lot of material, skilled labor, and time to construct. On the other hand, these buildings gain efficiency from the exterior walls' ability to serve simultaneously as both structure and enclosure. And the resulting structure is both strong and fire-resistant—characteristics that explain why so many centuries-old bearing wall buildings have survived and remain in beautiful condition today.
- ▶ The heavy timber frame is a structure in which stout wooden columns, beams, and braces form a discrete structural skeleton. Like bearing wall construction, the timber frame has its roots in distant antiquity. The earliest Greek temples were timber frame structures, and in more recent centuries, this system has been used in the traditional half-timbered houses of Europe and the classic American barn.
- ▶ As a structural system, the timber frame is similar to the bearing wall system, in that gravity loads are carried by the floor beams in **flexure** and then transmitted out to the building's perimeter. But here, unlike the bearing wall system, the load is concentrated in the four columns, which transmit it in compression down to the foundation, consisting of four column footings.
- ▶ Both wall footings and column footings have the same purpose: to spread out the weight of the structure as it's transmitted into the soil below.
- ▶ The heavy timber frame is a very versatile structural system, and it's generally less expensive to build than a traditional bearing wall building, particularly in regions with plentiful supplies of timber. But the all-wood construction of the timber frame is also less permanent, and its **mortise-and-tenon joints** require highly skilled craftsmen to fabricate.
- ▶ Bearing wall and timber frame structural systems have coexisted side by side—each with its own advantages and disadvantages—for many centuries. But the economic calculus of construction changed radically in the early 19th century.

- ▶ At that time, the advent of standardized mill-sawn lumber and machine-made iron nails stimulated the development of a fundamentally new structural configuration that rapidly superseded both the bearing wall and heavy timber frame systems. This new system, invented by a Chicagoan named George Washington Snow in the 1830s, was based entirely on the use of standard lightweight mill-sawn lumber held together with nails.
- ▶ Back then, critics derisively labeled it the **balloon frame**, because it seemed so unsubstantial and fragile, but Snow's light wood frame construction method proved to be surprisingly strong, while also providing better versatility and ease of construction at a much lower cost than either of its predecessors. It caught on quickly and, with only minor modifications, is still in use today as the dominant method of residential construction in the United States and Canada.
- ▶ The modern adaptation of Snow's balloon frame is called the platform frame. The dominance of the platform frame in modern residential construction does not render the other two structural systems irrelevant or obsolete. Both bearing wall construction and heavy timber framing have retained a significant presence in residential construction—and, indeed, have been staging a bit of a comeback in recent years.

TERMS

balloon frame: The original light wood frame structural system, developed by George Washington Snow in the 1830s. By exploiting the availability of standardized lightweight lumber and nails, the balloon frame revolutionized residential construction in North America.

beam: A structural element that carries load primarily in flexure or bending.

bearing wall construction: A structural system in which the principal vertical load-carrying elements are the exterior walls of the building.

column: A vertically oriented structural element that carries load primarily in compression.

compression: An internal force or stress that causes shortening of a structural element.

concrete: A mixture of Portland cement, sand, and gravel that hardens into a rocklike mass when mixed with water.

flexure: Bending of a structural element characterized by compression on the concave face of the element and tension on the convex face.

footing: A foundation element that distributes the weight of a structure to the soil below. Wall footings and column footings support walls and columns, respectively.

force: A push or pull applied to an object. A force is defined in terms of both magnitude and direction.

gravity load: A load caused by weight (e.g., of snow, occupants, furnishings, or the structure itself).

heavy timber frame construction: A structural system in which wooden columns, beams, and braces form a discrete structural skeleton.

joist: One of a series of parallel beams that directly support a floor or deck.

light wood frame construction: A structural system consisting of floor platforms and wall panels fabricated from multiple lightweight elements made of standard-sized lumber and fastened with nails.

live load: The weight of people, furniture, and other movable objects contained within a building.

mortise-and-tenon joint: A traditional method of joining beams and columns in a heavy timber framed structural system.

tension: An internal force or stress that causes elongation of a structural element.

torsion: The twisting of a structural element around its longitudinal axis.

READINGS

Allen, *Fundamentals of Building Construction*.

American Society of Civil Engineers, *Minimum Design Loads*.

Salvadori, *Why Buildings Stand Up*.

Wing, *The Visual Handbook of Building and Remodeling*.

QUESTIONS

- 1 Of the five principal types of load (dead, live, snow, wind, seismic), which one is most uncertain and variable? Which is most predictable?
- 2 How are these differences in the predictability of loads accounted for in structural design?

Platform-Framed Housing Construction

So far, you have learned about two of the three principal types of residential structural systems: bearing wall and heavy timber frame construction. In this lecture, you will learn about the third—light wood frame construction—which has dominated residential construction in the United States from the mid-19th century until today. The modern version of light wood frame construction is often called the platform frame. You will explore the platform-framed dwelling as a highly refined technological system—a standardized-but-flexible arrangement of lightweight modular floor platforms, wall panels, and roof trusses that carry load efficiently and are well suited for the integration of various building subsystems.

Platform Framing

- ▶ **Platform-framed construction** is a highly standardized system. In fact, seven chapters of the International Residential Code are largely devoted to detailed specifications governing every aspect of the platform-framing method, and most of the remaining chapters address the integration of electrical, plumbing, and building envelope systems with a platform-framed structure.
- ▶ Standardization of the method is also greatly facilitated by standardization of the associated materials. Throughout the United States, lumber is sold in standard sizes, such as 2-by-4, 2-by-6, 2-by-10, and so on. All commercially sold lumber also receives a standardized quality rating, recorded as a stamp on each piece of wood. Among other things, the stamp tells us the species of wood and the **grade** of the board.



platform-framed construction

The Foundation

- ▶ To help you understand what platform framing is and how it works, let's build a hypothetical single-family home from the ground up—much as your contractor would do the job. With its two stories, full basement, and gabled roof, this hypothetical house has all the key structural features necessary to illustrate the major elements of a platform-framed system.
- ▶ Even though platform framing is highly standardized, variations on the theme are nearly limitless. For example, a foundation might be made of concrete block or solid concrete, and a roof structure might use rafters or **trusses**. Platform framing can even be implemented in steel—for enhanced strength, fire resistance, and protection against insect damage.

- ▶ We'll start by surveying the building site and marking the locations of the foundation walls with wooden stakes and string lines. Guided by this survey, an excavator uses its hydraulically operated arm to dig the foundation excavation with great precision.
- ▶ Next, at the bottom of the excavation, wooden formwork is constructed for the wall footings and two interior column footings. A bed of gravel is placed at the bottom of these forms, and then the concrete is cast.
- ▶ Foundation walls can either be built up of concrete blocks, or they can be solid concrete that is cast in a single pour. We'll use the cast-concrete alternative for our project.
- ▶ After the footings have cured, wooden wall forms are set in place and very heavily braced—to withstand the substantial outward pressure that will be exerted by the wet concrete. A grid of steel reinforcing bars is then placed inside the forms.
- ▶ In modern practice, particularly for the construction of housing developments with large numbers of similar foundations, reusable steel forms are often used as an alternative to wood. In either case, the forms are set, such that the top of the foundation wall will be at least 6 inches above the final ground level—so that the wooden structure above will be less susceptible to rot.
- ▶ The concrete foundation walls are cast, using special inserts to form pockets, which will eventually support a steel **girder**. Before the concrete sets, steel anchor bolts are embedded into the top surface of the walls at regular intervals. These will provide the structural connection between the foundation and the wooden frame above.
- ▶ Once the concrete is cured and the forms are removed, we have a solid foundation wall. Then, the steel girder is placed in the pockets, and the steel pipe columns are prepared for installation. (The term “girder” refers to a main beam that supports other smaller beams or other structural elements.) The columns will be bolted to the footings below and to the beam above.

- ▶ A bed of gravel is placed over the entire basement floor to provide a base for the concrete floor slab. Before pouring the slab, we put down a sheet of polyethylene plastic (a moisture barrier) and then a mesh of steel wire reinforcement. Finally, with the concrete floor slab in place, our foundation is complete and ready for construction of the first-floor platform.

First- and Second-Floor Platforms

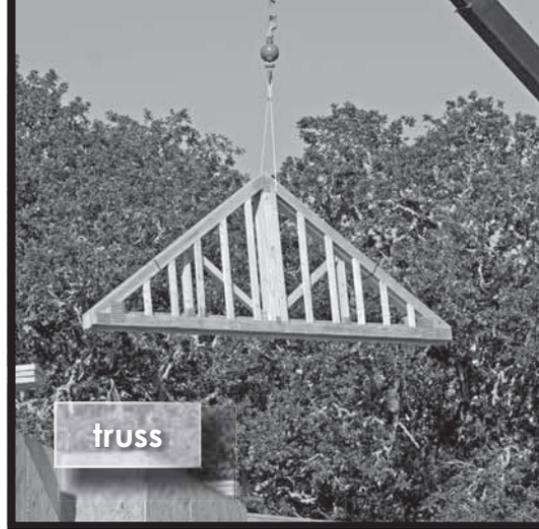
- ▶ We'll now build the first-floor platform, the structural subassembly that gives platform framing its name. We begin by bolting a wooden sill plate to the anchor bolts protruding from the top of the foundation walls. This is the base on which the entire platform frame will be assembled.
- ▶ The floor platform is constructed of parallel beams, called joists, usually spaced 16 inches apart. A board, called a rim joist, caps the joists' outside ends and holds them in a vertical orientation. At their inner ends, the joists are overlapped above the central girder.
- ▶ Wherever there are large openings through the floor—for a stairwell, for example—elements called trimmer joists and **headers** are added to frame the opening.
- ▶ Next, we can install the structural **subfloor**—made of plywood or, its more recent alternative, **oriented strand board (OSB)**, which is fabricated from random wood fibers glued together under high pressure, unlike the discrete laminations used in plywood.
- ▶ These 4-by-8-inch sheets are nailed onto the tops of the joists and headers in a staggered pattern. If the carpenters have done their job well, the subfloor panels will line up perfectly with the joists, so very little trimming is required.
- ▶ Next, we can backfill the foundation excavation with compacted soil. We didn't do it sooner because the lateral pressure of the soil might have

tipped the foundation walls inward. Now, with the first-floor platform installed, there's no danger of this happening, so we can proceed with construction of the first-story exterior walls.

- ▶ In a platform-framed structural system, each wall is composed of parallel studs, typically 2-by-4s spaced 16 inches apart, nailed together with a sole plate across the bottom and a pair of top plates above. At the top of each window and door opening is a solid wooden beam called a header.
- ▶ These wall panels are usually assembled horizontally, lying on the subfloor that we just finished installing. Once a wall is fully framed, it's tilted up and into position along the edge of the floor platform and held in place with temporary diagonal braces. After all walls are erected and their alignment has been carefully checked, they're nailed permanently into position and then covered with **sheathing** made of plywood or oriented strand board.
- ▶ Most houses are too wide for floor joists to span safely from one outer wall to the other. Thus, one or more load-bearing partition walls are nearly always required in the framing plan. The load-bearing wall serves the same structural function as the steel girder below the first floor, except the load-bearing wall supports only loads applied to the second floor and above.
- ▶ Most houses also have non-load-bearing partition walls, which subdivide the interior space but don't support the floor above. These walls usually aren't erected until after the next-floor platform has been added overhead.
- ▶ We can now add the second-floor platform, walls, and ceiling structure using the same methods we used for the first floor. One of the most important advantages of platform framing is that this process can be accomplished without cranes or scaffolding, because each new floor platform provides a solid working surface on which the builders can fabricate the next-higher story.

The Roof

- ▶ Finally, we add the roof structure, which consists of ceiling joists, a ridge board, and angled beams called rafters, covered with roof sheathing. Under gravity load, rafters bend. To prevent the rafters from breaking, building codes require a strong structural connection between the outer ends of the rafters and the ceiling joists. The resulting triangular structure is called a truss, and it is an efficient system for carrying gravity loads while also providing sloped roof surfaces that shed rainwater and snow.



- ▶ In recent years, builders have begun replacing this simple combination of rafters and ceiling joists with more elaborate prefabricated roof trusses that are custom designed, factory built of lightweight lumber, and held together with metal nailing plates. They create an amazingly strong joint, and they're assembled with considerably less effort than the precision-made mortise-and-tenon joints used in the heavy timber frame. By code, these trusses must be designed by a licensed engineer, but the investment in design pays off in greatly enhanced structural efficiency.

The Platform-Framed Structural System

- ▶ The platform-framed structural system carries load in the following way.
 - Snow load is applied to the roof sheathing and then transmitted through the trusses to the exterior walls, then down through the wall panels, foundation walls, and footings into the soil below.

- Simultaneously, live load is applied to interior floors and then transmitted through the joists to both the exterior and interior walls—with the interior load path passing through a steel girder, interior columns, and column footings before finally reaching terra firma.
- Wind and seismic loads are carried by the wall panels themselves.
- ▶ This beautifully engineered system has flourished through nearly two centuries of refinement, adaptation, optimization, and innovation for three reasons.
 - It is highly economical, because it uses lightweight, standard-size lumber that can be worked with common tools and assembled with simple fasteners; it can be erected without cranes or scaffolding; and manufacturers have created thousands of products that have been purposefully designed for compatibility with it.
 - It is a highly flexible system that can be applied to an incredible variety of architectural styles.
 - It provides a solid framework for effective integration of the building's other engineered subsystems.

TERMS

girder: A main beam to which load is transmitted from other elements of a structural system.

grade: (1) A standardized quality rating for commercial lumber. Higher grades of wood have fewer defects and, thus, higher strength. (2) Ground level (as in slab on grade and railroad grade crossing). (3) The slope of a surface, typically measured as a ratio of vertical to horizontal distance and expressed as a percentage. Also called a **gradient**.

header: A structural element used to frame an opening in a floor platform or wall panel.

oriented strand board (OSB): An engineered wood panel formed by compressing layers of wood strands and adhesive. OSB often serves as a substitute for plywood in modern residential construction.

platform-framed construction: The most common form of modern light wood frame construction, named for the modular floor platform that serves as a base for the construction of each story.

sheathing: A structural sheet—normally plywood or oriented strand board—that covers the outside of a wall panel or roof framing in platform-framed construction.

subfloor: A structural floor panel that is normally made of plywood or oriented strand board and is supported on joists.

truss: A structural system composed of slender elements arranged in interconnected triangles. Truss elements carry load primarily in tension or compression.

READINGS

Allen, *Fundamentals of Building Construction*.

International Code Council, *2015 International Residential Code*.

Wing, *The Visual Handbook of Building and Remodeling*, chapters 5–7.

QUESTIONS

- 1 Why is the platform-framed structural system so common in North America?
- 2 What are some disadvantages and limitations of platform framing?

The Building Envelope

In this lecture, you will learn about the building envelope: a layered system of roof, wall, and foundation elements designed to serve as an integrated barrier against the movement of water, air, and heat into and out of the building's interior space. If a building envelope is working properly, it sheds rainwater and conveys it away from the building's foundation, prevents melting snow and ice from penetrating the roof or walls, prevents groundwater from infiltrating through the foundation, facilitates the removal of internally generated water vapor, minimizes the transmission of heat into the building in the summer and out of the building in the winter, and provides fire resistance.

The Building Envelope

- ▶ Water can potentially damage your home in all three of its phases—liquid, gas, and solid—as precipitation, groundwater, water vapor, snow, and ice. The principal mechanism by which precipitation moves is gravity. As rainwater strikes the roof and walls of your house and then follows its gravity-driven path downward to the ground, it has an amazing capacity to find gaps—between shingles, between siding boards, and at penetrations where windows, doors, or vents pass through the building envelope. Each of these gaps is a potential leak.
- ▶ The building envelope includes two principal lines of defense against such leaks. The first is an outer protective layer, consisting of shingles on your roof and **cladding** on your walls. The shingles might be asphalt, fiberglass, wood, slate, or **clay** tiles, and the cladding might be brick, stone, stucco, or siding. Regardless of material or configuration, all of these elements work in essentially the same way: Precipitation impinges on them, and as the water flows downward, it's also directed outward.

- ▶ The second line of defense against leaks is an underlying water-resistant membrane. As helpful as that outer layer might be, it can never be fully effective as a water barrier. As a result, the outer protective layer always must be backed up by a water-resistant membrane that fully encloses and protects the structural system.
- ▶ Furthermore, this membrane is regarded as the building's primary water barrier. Shingles and cladding provide supplemental protection against water infiltration, but their more important purpose is to protect the water-resistant membrane from damage, which might be caused by wind, snow, ice, ultraviolet radiation, or critters.



tar paper

- ▶ On the roof, this water-resistant membrane is usually made of a material called tar paper, or roofing felt. In the 19th century, this material was heavy paper coated with tar, but today, it's made of a much sturdier polyester or fiberglass fleece that is impregnated with an asphalt sealer.

The Roof System

- ▶ To assemble a roof system, we begin by installing an aluminum fitting called a **drip edge** along the eaves. Then, we add the overlapping sheets of the membrane. Along the inclined edge—called the **rake** of the roof—we install another drip edge, which will prevent wind-driven rain from penetrating underneath the membrane.
- ▶ Next, we simultaneously add the shingles and associated **flashing**—strips of sheet metal configured to prevent leaks at intersections and penetrations. The shingles are nailed to the roof sheathing, starting at the eaves and working upward, with each row overlapping the one below it, with each nail passing through two layers of shingles, and with the nail heads subsequently covered by the overlapping shingle above. One final row of specially cut shingles is draped over the ridge, with no exposed seams pointing uphill.
- ▶ The flashing installation must be carefully integrated with the shingles to ensure that there are no possible pathways for water to enter the gaps that the flashing is intended to seal.
- ▶ We now have an integrated roof system that will shed any precipitation falling on it, but the building envelope's work isn't complete until the water is captured, directed down to the ground, and conveyed away from the perimeter of the house.
- ▶ This is the job of our aluminum rain gutters, which are attached to a vertical board, called the fascia, and sloped very gently downward toward downspouts at each corner of the building. With the gutters in place, the whole roof system works. No matter where a raindrop falls, it will follow a downhill path that leads to a gutter and then to the ground.

- ▶ To defend against leaks resulting from **ice dams**—a solid wall of ice that can form within and above the rain gutter when a roof is covered in snow—use a product called ice and water shield as a substitute for roofing felt along the lower edge of the roof. Ice and water shield is a more robust membrane with a self-sealing rubberized asphalt coating and a self-adhesive backing, so it can be attached to the roof sheathing without nails.

The Exterior Wall System

- ▶ Like the roof, a well-designed exterior wall system has two lines of defense against water infiltration: an inner water-resistant membrane attached directly to the sheathing and an outer protective layer called cladding.
- ▶ Water-resistant wall membranes used to be made of tar paper, just like the stuff on the roof. Today, the International Residential Code still allows the use of asphalt-impregnated felt for this purpose, but felt has largely

been superseded by a new technology called **housewrap**, which is most commonly composed of fine polyethylene fibers bonded together by heat and pressure during the manufacturing process.

- ▶ Housewrap is installed by nailing or stapling it to the wall sheathing in overlapping horizontal strips, just as roofing felt is installed on the roof sheathing. This process is simple on a plain wall, but at windows, doors, and other penetrations, observing the rule that no exposed seams can point uphill becomes much more complicated.
- ▶ With the membrane in place, we can now install the cladding—an exterior veneer of brick, stone, stucco, or siding. If it's siding, it might be wood, vinyl, aluminum, or a recently developed composite material called fiber cement. One of the more common combinations is a brick façade on the front wall and vinyl siding everywhere else.
- ▶ Before the vinyl siding can be installed, trim pieces are mounted around all windows and doors and at the corners of the building. These will cover up the edges of the siding while also allowing for expansion and contraction with changes of temperature.
- ▶ The siding panels are installed directly over the housewrap from bottom to top. Each panel is nailed only at its top edge, while its lower edge is held in place by an overlap with the panel below. The uppermost panel is capped with a piece of flashing that prevents water infiltration at the top of the cladding while also hiding the nails that hold the panel in place.
- ▶ For the portion of the wall that will be clad with brick, the brick veneer rests directly on the concrete foundation wall, with a one-inch airspace between its rear surface and the drainage plane. The veneer is supported laterally by galvanized steel ties, which are nailed to the wall studs and embedded in the mortar joints between bricks.
- ▶ The metal flashing is tucked beneath the housewrap at its upper end and extends through the full thickness of the brick at its lower end, where **weep holes** are created by leaving a gap in the vertical mortar joint at every third brick.

- ▶ The brick veneer sheds most rainwater, but if any moisture does penetrate through cracks or gaps, it merely flows down the drainage plane, or housewrapped surface, and is channeled by the bottom flashing back out through the weep holes. The airspace also facilitates air circulation, which allows the system to dry out between storms.

The Foundation

- ▶ Although we've successfully enclosed our roof and walls, potential problems with water infiltration can extend underground, where keeping the building dry can be even more challenging because, below ground, water doesn't always flow downhill.
- ▶ The two principal mechanisms for transmission of groundwater—rainwater that percolates down into the soil—through a building foundation are **hydrostatic pressure** and **capillary action**. Hydrostatic pressure is pressure caused by the water's own weight. At a given point, hydrostatic pressure acts equally in all directions, and it always acts perpendicular to the surface of a submerged object.
- ▶ There are two principal defenses against water infiltration due to hydrostatic pressure. The first is to prevent cracking of the foundation walls by using high-quality concrete with steel reinforcement, as specified by the building code; the second is to prevent groundwater from accumulating around your foundation.
- ▶ The second mechanism by which groundwater may penetrate the building envelope is capillary action: the tendency of a liquid to be drawn into a fine-grained or finely divided solid—including concrete. Even in the absence of hydrostatic pressure, groundwater can be drawn up into concrete footings and floor slabs, then into the foundation walls, and ultimately into the wooden wall cavity, where prolonged exposure to moisture can cause rot and promote the growth of mold.
- ▶ The best defense against this malady is to use a capillary break to prevent water from being drawn into the foundation. Current codes

require a polyethylene plastic sheet directly beneath the floor slab and a damp-proof coating or membrane applied to the exterior surface of the foundation walls.

Defending against Water Vapor

- ▶ Surprisingly, water vapor—the gaseous form of water—can be at least as damaging to your house as liquid water, because it can accumulate inside wall cavities and promote rot and mold. Most of the water vapor in a home is generated by the occupants: taking showers, boiling water, and breathing. Most commonly, water vapor gets into wall cavities through air leaks.

- ▶ A well-designed building envelope should include four principal defenses against water vapor accumulating in wall cavities.
 - It should collect as much moisture as possible at its source and move it directly out of the building.

 - Airflow through the building envelope should be minimized by caulking around windows, doors, wall penetrations, and other gaps.

 - The building envelope should include a **vapor** barrier to reduce the amount of moisture entering the walls.

 - Recognizing that some moisture will inevitably get into the walls no matter what, the envelope should have a permeable face on the opposite side of the vapor barrier to allow the walls to dry out.

Insulation and Drywall

- ▶ Insulation reduces the transmission of heat from inside to outside in the winter and from outside to inside in the summer. For many decades, the standard insulating material used in U.S. residential construction has been **fiberglass batting**, consisting of a mat of glass fibers with a craft-paper backing.

► Today, fiberglass remains in common use, but greater public interest in energy efficiency has stimulated the development of new high-performance insulations, sealants, windows, and doors—which have taken energy-efficient building design to a new level.

► We close up our interior walls with gypsum wallboard, also called **drywall**—a panel made of gypsum plaster sandwiched between two sheets of thick paper. Drywall is screwed to the studs and joists and then taped and spackled to create smooth interior wall and ceiling surfaces that look good, add a bit more insulating value, and significantly enhance the fire resistance of the wooden structural frame.



TERMS

capillary action: The tendency of a liquid to be drawn into a fine-grained or finely divided solid.

cladding: The outer layer of a building envelope, typically consisting of brick, stone, stucco, or siding.

clay: An extremely fine-grained soil formed from the weathering of silicate-bearing rocks. Clay is highly cohesive—capable of holding its shape without crumbling—and impervious to water.

drip edge: Metal flashing applied to the edges of a roof to prevent water from infiltrating beneath the protective roof membrane and to direct rainwater into the rain gutters.

drywall: A panel composed of gypsum sandwiched between two layers of cardboard that is used as a fire-resistant inner layer of the building envelope.

fiberglass batting: A common form of thermal insulation used in residential construction.

flashing: A strip of sheet metal or plastic configured to prevent leaks at intersections and penetrations in wall and roof surfaces.

housewrap: A plastic sheet used to prevent water infiltration through a building envelope.

hydrostatic pressure: Pressure caused by the weight of water. Hydrostatic pressure acts uniformly in all directions. Where water is in contact with a submerged body, hydrostatic pressure acts perpendicular to the surface of the body.

ice dam: An accumulation of ice at the edge of a roof. Water from melting snow and ice can back up behind the ice dam and cause leaks through the roof membrane.

rake: The inclined edge of a peaked roof.

vapor: The gaseous phase of a substance.

weep holes: Openings at or near the bottom of a masonry wall to allow for drainage of any water that penetrates the cladding.

READINGS

Johnston and Gibson, *Green from the Ground Up*, chapters 6 and 12.

Wing, *The Visual Handbook of Building and Remodeling*, chapters 7–9.

QUESTIONS

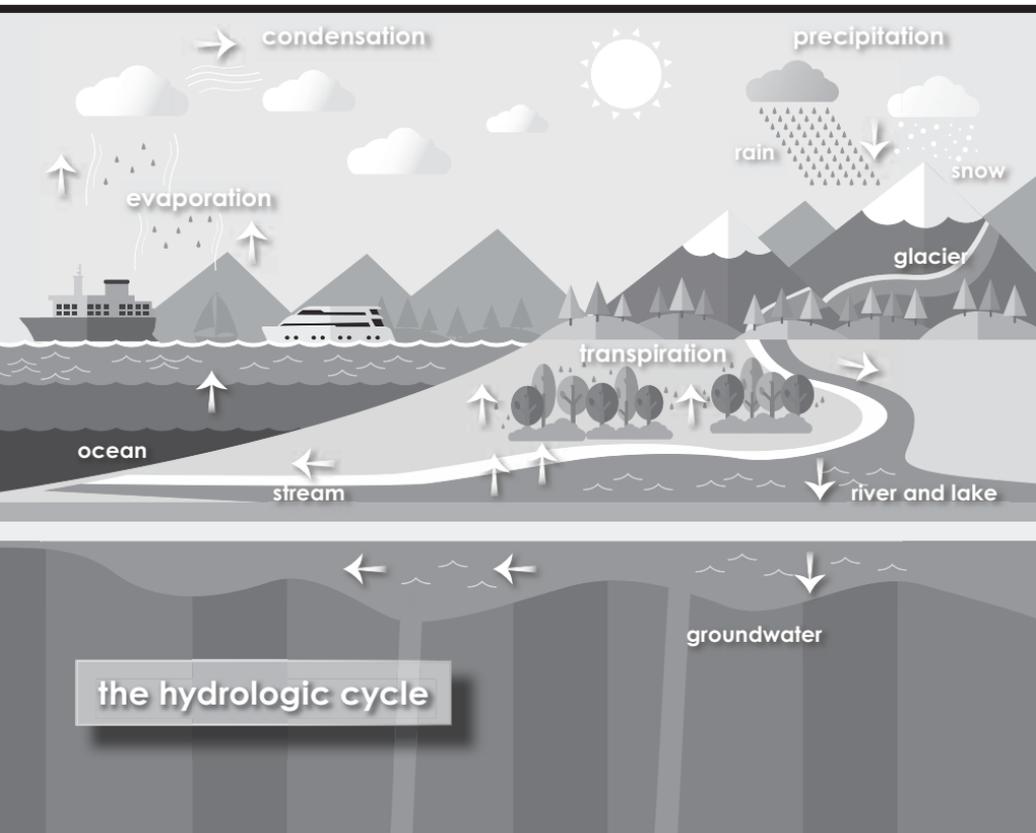
- 1 While viewing your home from outside, identify five specific locations where water leaks might occur.
- 2 At these locations, what is currently preventing leaks from happening?

The site design process, typically performed by civil engineers, can be applied to a single building lot, but it's most often applied to an entire development, consisting of multiple residential or commercial properties. The site design for a development deals with all aspects of physical layout and integration with local civil infrastructure systems. A site design also can be significantly influenced by such considerations as environmental impact, historic preservation, zoning, and real estate—and, for this reason, it's usually very tightly regulated by local codes. This lecture will focus primarily on the storm drainage design and earthwork elements of site design.

Hydrology and Hydraulics

- ▶ In the world of everyday engineering, we encounter water in many different forms. But regardless of whether we're talking about supplying purified drinking water to your home, dumping household wastewater into your municipal sewer system, diverting storm runoff away from your foundation, or pumping groundwater out of your basement, we'll always deal with water by applying underlying scientific concepts from two specialized disciplines of engineering science called **hydrology** and **hydraulics**.
- ▶ In the context of storm drainage design, the easiest way to distinguish between these two fields is that the science of hydrology helps us define the problems while the science of hydraulics helps us devise technological solutions to these problems.
- ▶ Hydrology is the study of the natural movement and distribution of water above, on, and below the surface of the Earth. This science is best understood in the context of the hydrologic cycle, a conceptual model describing the continuous circulation of water in the atmosphere, on the Earth's surface, and underground.

- ▶ Although water covers about 70% of the Earth's surface, only about 0.1% of it has any chance of directly influencing everyday engineering. This relatively small quantity of water originates as precipitation, which **condenses** from water vapor in the atmosphere and falls to the ground in the form of rain, sleet, or snow. Some of this water percolates down into the soil and is eventually collected in porous underground strata called **aquifers**. This water is called groundwater.
- ▶ The remaining water from precipitation flows over the Earth's surface—initially in a thin layer called sheet flow, which moves downhill, across the surface of the ground—and then eventually concentrates in ditches, streams, rivers, lakes, and oceans. Along the way, some of this surface water evaporates, thus returning to the atmosphere, where the hydrologic cycle begins anew.





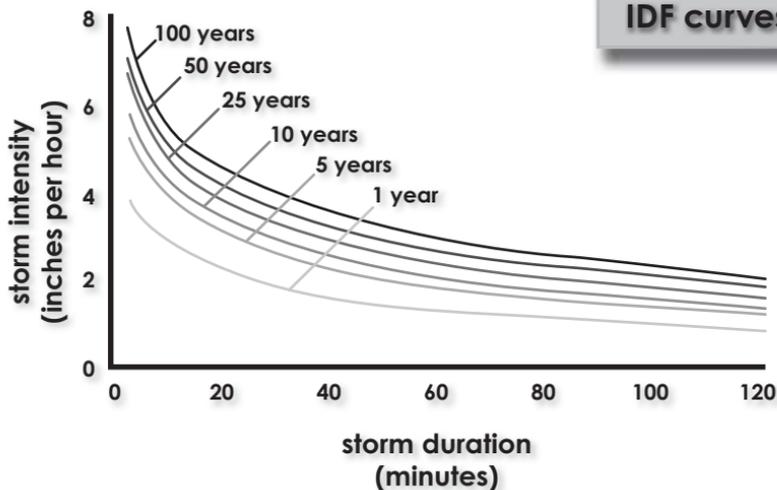
Poor drainage can lead to flooding and foundation damage.

- ▶ Storm drainage design is primarily concerned with surface water. And while it constitutes a tiny proportion of the Earth's water supply, it can cause big problems for homeowners and developers. If precipitation that falls on your lot isn't directed away from your house, some of it will seep into the soil around your foundation and may find its way into your basement. And if your lot adjoins higher ground, storm runoff will generally flow from that ground onto yours, exacerbating the challenge of conveying surface water away from your foundation.
- ▶ Furthermore, anytime land is developed, large areas of porous ground are covered over with impervious pavements and rooftops. As a result, significantly less precipitation infiltrates down into the soil and significantly more flows over driveways and streets. This increased surface flow can cause flooding, inundation of municipal **storm sewers**, and the depletion of groundwater (which might be used for local water supply).
- ▶ Storm runoff also can become polluted, accumulating metals from gutters and downspouts, hydrocarbon residue from pavements, and fertilizers and pesticides from lawns.

- ▶ Storm drainage design must address all of these challenges, primarily through hydraulics, a scientific field that's broadly concerned with the **mechanical properties** and engineering applications of fluids. The hydraulics concepts most relevant to everyday engineering are mathematical models used to characterize the flow of water through closed pipes, such as water supply lines, and through open channels, such as ditches and river valleys, both natural and manmade.

Designing a Storm Drainage System

- ▶ To illustrate how hydrology and hydraulics have influenced the piece of terrain on which your home is situated, let's walk through the process a civil engineer would use to design a **storm drainage system** for a typical suburban land development project.
- ▶ After obtaining a topographic map of the project site (from the U.S. Geologic Survey website for places in the United States), we can execute the first step in the storm drainage design process: delineating the **watershed** for our proposed development project. A watershed is an area of land defined such that a drop of rainwater falling anywhere within its boundaries eventually drains to the same **outlet**.
- ▶ A watershed can be very large or very small, and the large ones can be subdivided into an infinite number of smaller ones. A watershed also can be defined for a specific project site—although, at this small scale, it's often called a catchment. Regardless of size or terminology, the delineation of a watershed always derives from the point designated as the outlet.
- ▶ Next, we'll define something called the **design storm**, which will serve as the basis for designing the entire drainage system. The design storm typically is defined in the form of a graph called an intensity-duration-frequency (IDF) curve. Each region in the United States has its own characteristic set of IDF curves, which are developed by the National Oceanic and Atmospheric Administration from long-term statistical data on storms experienced within the region.



- ▶ Each plot shows the relationship between storm intensity (measured in inches of rainfall per hour) and storm duration (in minutes) for a representative storm with a particular recurrence interval—100 years, 50 years, 25 years, and so on. The recurrence interval is the statistical average period of time between occurrences of a storm with a particular severity. Thus, for example, a storm with a 100-year recurrence interval will happen, on average, once every 100 years.
- ▶ In general, a storm with a longer recurrence interval is both more severe and less probable than a storm with a shorter recurrence interval, and a storm of short duration has a higher intensity than a storm of longer duration. Local building codes usually specify which recurrence interval is to be used for storm drainage design in the associated jurisdiction.
- ▶ Next, we can perform a hydrologic analysis of the catchment area using a standard analytical technique called the **rational method**. At the heart of the rational method is a mathematical equation, $Q = CiA$, which is used to calculate the maximum rate of storm runoff that will flow through the outlet of the drainage system during the design storm.

- ▶ The maximum runoff, Q , is measured in cubic feet per second and is also called the discharge of the watershed. A is the area of the watershed in acres. C is called the runoff coefficient, an empirically derived parameter that's based on the permeability of the ground surface within the watershed. Finally, i is the intensity of the design storm in inches of rainfall per hour.

Adding a Storm Sewer System

- ▶ If all the extra water brought in from a storm isn't properly managed, it's going to cause two major problems. First, during heavy storms, torrents of water flowing over the road surfaces within the development are going to cause a safety hazard for drivers. The design engineer will address this challenge by incorporating a storm sewer system into the site design.
- ▶ A storm sewer is a network of underground pipes that collect storm water and convey it to a nearby watercourse, lake, or ocean. The storm runoff enters the system through inlet structures. Above ground, the inlet is typically a steel grating or curb opening. Below ground is a precast concrete box with large holes to accommodate the incoming and outgoing pipes.
- ▶ The pipes are often concrete, although iron, steel, and plastic are sometimes used, as well. They run from inlet structure to inlet structure, arranged in a treelike network, with small branches feeding into larger trunks and those feeding into even larger main lines. All pipes in the system are placed on a steady downhill slope, so water will flow through the system by the force of gravity alone.
- ▶ In designing this system, we would first determine appropriate locations for the inlet structures. These are placed, at a minimum, at low points in the road network to prevent water from pooling and immediately uphill of intersections so that storm runoff doesn't create a safety hazard by flowing across the intersection. Additional inlets often are added at regular intervals to intercept the flow so that the inlet structures at the low points don't get inundated in large storms.

concrete drainage tank



- ▶ With the inlets positioned, the science of hydraulics provides us with all of the analytical tools necessary to determine the size of each pipe, such that it can carry the accumulating discharge from inlets and from higher-level pipes, and the slope of each pipe, such that the velocity of flow is high enough to prevent sediment from accumulating in the pipe.

Adding a Storm-Water Detention Pond

- ▶ Our project site has a new storm sewer system to keep water off the streets within the residential development, but we still need to contend with a second major challenge: the substantial increase in discharge at the outlet.
- ▶ A partial solution would be to route the discharge in a catch basin and carry it directly to a stream through a large underground pipe. At the termination of this pipeline, we'd add an outfall structure that is designed such that any sediment being carried along by the storm water will be deposited into a bed of coarse stone rather than being dumped into the stream.
- ▶ But this pipeline is only a partial solution, because our development has increased the total discharge from this watershed by a significant amount. Dumping all this additional water into the stream will only increase the likelihood of flooding downstream. And with each new housing development, shopping mall, and business park, the likelihood of flooding is only going to increase.
- ▶ For this reason, today many municipal codes specify that the maximum postdevelopment storm discharge can't exceed the predevelopment discharge. But how is this possible, given that development always causes runoff to increase?
- ▶ The answer is to incorporate a storm-water detention pond into the site design. A detention pond is an earthen enclosure, typically located near the outlet of the development's storm drainage system. Storm

drains discharge into the basin at outlet structures. The basin stores the runoff temporarily, allowing some to infiltrate into the soil and some to evaporate. Peak runoff from large storms is released at a controlled rate, from an outlet structure into a local watercourse or an existing storm sewer line.

- ▶ In recent years, there has been growing awareness of the pollution that storm runoff accumulates from roofs, yards, and parking lots. In response, many local standards for detention ponds also require water treatment.

Grading the Site

- ▶ In addition to a storm sewer system and a detention pond, our design must also provide pathways for precipitation that falls on rooftops and unpaved areas to flow overland to the storm sewer inlets without flooding basements, creating unwanted ponds, eroding hillsides, or flooding streets.
- ▶ To a large extent, this need is fulfilled through **earthwork**, also called **grading**. In general, grading re-forms the topographic contours of the project site for compatibility with the intended land use. We'll meet this challenge by grading the site to modify the pattern of overland flow.
- ▶ The grading plan works in tandem with the storm sewer, street, and detention pond designs, fundamentally altering the movement of precipitation across and underneath the project site—all for the purpose of moving water away from our homes.

TERMS

aquifer: A porous stratum of soil or rock in which groundwater collects.

condense: To change from the vapor phase to the liquid phase.

design storm: A hypothetical rainstorm with characteristic, statistically derived intensity (measured in inches of rainfall per hour); duration (measured in minutes); and frequency (represented as a recurrence interval in years) that is used as the basis for hydrologic analysis using the rational method.

earthwork: The process of re-forming the topographic contours of a project site for compatibility with the intended land use. Also called **grading**.

grading: The process of re-forming the topographic contours of a project site for compatibility with the intended land use. Also called **earthwork**.

hydraulics: A scientific field that is broadly concerned with the mechanical properties and engineering applications of fluids.

hydrology: The scientific study of the natural movement and distribution of water above, on, and below the surface of the Earth.

mechanical properties: Characteristics of a material that describe how the material responds to forces.

outlet: The point at which storm runoff departs from a watershed.

rational method: An analysis methodology for calculating maximum rate of storm runoff (measured in cubic feet per second) from a watershed during a specified design storm.

storm drainage system: An engineered system that captures the surface runoff resulting from precipitation and channels it into a natural watercourse.

storm sewer: A network of underground pipes that collects storm water and conveys it to a nearby watercourse, lake, or ocean.

watershed: An area of land defined such that a drop of rainwater falling anywhere within its boundaries eventually drains to the same outlet.

READINGS

Dewberry, ed., *Land Development Handbook*, chapters 1, 21, 22, and 24.

Hayes, *Infrastructure*, chapter 2.

Wing, *The Visual Handbook of Building and Remodeling*, chapter 2.

QUESTIONS

- 1** From a suitable vantage point outside your home, observe the contours of the land surrounding your residence. Can you visualize the flow of storm runoff across the land?
- 2** Does storm runoff from the vicinity of your home flow into a storm sewer system? If so, can you identify the storm sewer inlets? Where is this water discharged into a natural watercourse?

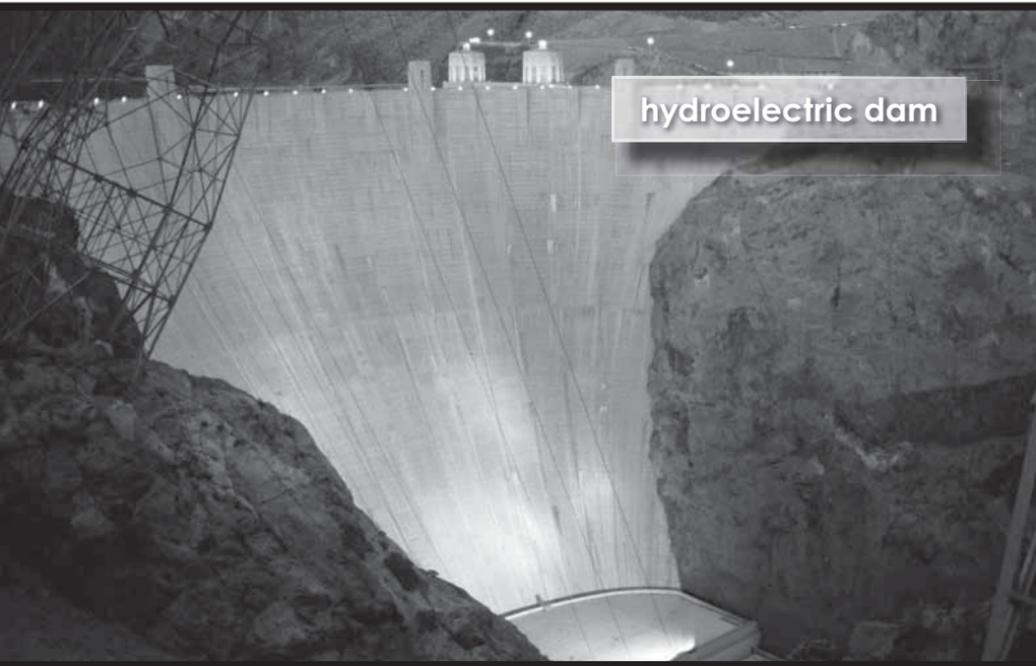
Dam, Reservoir, and Aqueduct Design

Practically from the dawn of civilization, humans have obtained groundwater by tapping into underground aquifers. In the ancient world, groundwater sources—wells and springs—were generally preferred over surface water, but today, surface water is the principal source for most large-scale water systems. A water supply system for a large urban population typically includes six major elements: a watershed, a raw water collection point, a conduit through which water is transmitted from the collection point to its point of use, a water purification facility, water storage facilities, and a water distribution network. This lecture focuses on collection and transmission.

Watersheds

- ▶ A watershed is an area of land delineated such that a drop of rainwater falling anywhere within that area eventually drains to the same outlet. Thus, a watershed serves the very useful function of collecting the precipitation falling on a large area of land and then concentrating it in a single watercourse, where it can serve as the source for a water supply system.
- ▶ A given watershed will be adequate as a water supply for a city or town if the quantity of water discharged from the watershed exceeds the current and anticipated future demands of the population being supplied. The demand on a municipal water supply system is typically estimated as about 150 gallons per person per day. Most of this water flows through our dishwashers, washing machines, sinks, toilets, tubs, and showers.
- ▶ Some cities are able to meet this huge demand by drawing water directly from major rivers or lakes. In most cases, however, the quantity or quality of a municipality's local water supply is inadequate, and it must look to a watershed some distance away—often in a less-developed region with fewer sources of pollution.

- ▶ And even if a given source provides an adequate quantity of water on an annual basis, seasonal variations in rainfall (and, therefore, in stream flow) might cause shortfalls at certain times of year. To cope with seasonal variations, the typical urban water supply system uses a **dam** to create a storage reservoir, which receives a variable inflow but holds enough water to provide a steady outflow.



Dams

- ▶ A dam is an engineered structure designed to impound water, generally by blocking the flow of a natural watercourse. A dam creates a reservoir and also must control the release of water from that reservoir. Dams are used for water supply, irrigation, flood control, and the generation of **hydroelectric power**. Many dams serve several of these purposes simultaneously.

- ▶ A dam is generally classified according to two characteristics: its principal construction material (concrete, masonry, soil, or rock) and its structural configuration (**arch dam** or **gravity dam**).
- ▶ When an **arch** is used in a bridge or a building, it's oriented vertically, and loads are applied vertically, as well. The arch carries load primarily in compression, and it can carry a tremendous amount of load, provided that two conditions are satisfied: It must be made of a material, such as concrete or stone, that's very strong in compression, and it must be laterally supported at its base to restrain the ends' natural tendency to spread outward under load.
- ▶ The other major structural configuration is the gravity dam, which attains its structural load-carrying capacity primarily from its mass. There are two principal types of gravity dams, based on whether the construction material is concrete or masonry, or soil or rock.
- ▶ Monumental concrete dams are impressive structures, but at the opposite end of the technological spectrum, there are gravity dams that are, in many ways, even more fascinating. These structures are made of the least sophisticated structural materials available—soil and rock—but involve surprisingly sophisticated engineering. They're called the **earth dam** and the **rock-fill dam**.
- ▶ How do engineers decide which type of dam to use in a given situation? In general, concrete dams are preferable to earth and rock-fill dams when the reservoir needs to be very deep—a situation that's usually dictated by the topography of the valley, the required water storage capacity, or the need to generate hydroelectric power.
- ▶ Topography also has a major influence on a dam's structural configuration. A deep, V-shaped valley with solid rock walls is ideal for an arch dam. A somewhat wider valley with high walls would favor a concrete or rock-fill gravity dam. A broad, low valley would generally call for an earth dam, particularly if the valley floor were covered with a deep layer of alluvial soil, because earth dams don't necessarily have to be constructed on bedrock, as concrete dams do.

Aqueducts

- ▶ An aqueduct is a conduit used to transport water from its source to its point of use—typically a city or town. This water channel can use any of four basic configurations, depending primarily on the terrain being traversed. We can explore all four configurations by examining a single real-world system: the Catskill Aqueduct, a 92-mile conduit that carries about 40% of New York City’s water supply from an upstate watershed to the city.
- ▶ Built between 1907 and 1917, the Catskill Aqueduct draws its water from a 123-billion-gallon reservoir formed by a 4650-foot dam across the Esopus Creek near Olivebridge, New York. Driven entirely by gravity, up to 600 million gallons of water flow through this aqueduct every day. It crosses five major geological regions and the Hudson River, while surrendering less than 300 feet of elevation over its entire 92-mile length.
- ▶ The conduit ends at the 900-million-gallon Hillview Reservoir in Yonkers, New York, where its water is fed into the city’s equally impressive **water distribution** network. This receiving reservoir serves two functions: It provides a reserve of several days’ water supply, in case the aqueduct needs to be temporarily



shut down for maintenance or repair, and it also accommodates the continuously changing differences between the aqueduct's relatively steady inflow and the city's hour-by-hour variations in demand—with purposeful consideration of the need to supply a huge quantity of water quickly in the event of a large fire.

- ▶ There are four distinctly different channel configurations constituting the Catskill Aqueduct. There's the dam and reservoir, and with the **outlet works** open, water flows into the first channel configuration, called cut-and-cover segments, constituting 55 miles (or about 60%) of the aqueduct's total length.
- ▶ The cut-and-cover channel in the Catskill system was built by cutting a shallow trench into the soil, casting a horseshoe-shaped concrete tube, and then covering the tube with a soil embankment. Longitudinally, this channel is constructed on a constant downhill slope of one foot of elevation for every mile of length, following the contours of the Earth as necessary to maintain this **gradient**.
- ▶ Next, 15% of the Catskill Aqueduct consists of **grade tunnels**, which carry the channel through mountains of solid rock at 23 different locations along the route. The irregular tunnel opening was reinforced with a concrete liner, using essentially the same horseshoe shape in the cut-and-cover channel, though somewhat narrower to reduce the required amount of rock excavation. To keep this narrower channel from constricting the flow, its slope was doubled to 2 feet per mile. This increased gradient causes the water to flow faster, thus compensating for the reduction in channel size at the grade tunnel locations.
- ▶ In the science of hydraulics, the movement of water in both cut-and-cover conduits and grade tunnels is classified as **open-channel flow**. This might seem odd, because both of these channel configurations are fully enclosed, but the technical definition of open-channel flow requires only that the moving fluid has a free surface. In other words, the conduit flows only partially full, with the water surface at atmospheric pressure.

- ▶ To maintain its flow, an open channel requires a steady downhill gradient—just as with the cut-and-cover and grade-tunnel segments of the Catskill Aqueduct. The concrete covers over these channels don't have any effect on the flow within; rather, they serve only to protect the water from evaporation and contamination.
- ▶ In contrast, the remaining two configurations used in the Catskill Aqueduct are characterized by true **pipe flow**, with their conduits flowing full and under pressure—and, thus, with no requirement for the channel to assume a continuous downhill gradient.
- ▶ One of these two pipe-flow segments is the **inverted siphon**, whose purpose is to transmit water across a valley with a pipeline placed at ground level. Water will flow through an inverted siphon—even though a portion of its journey is uphill—as long as the upstream water level is higher than the downstream water level. This elevation difference supplies the pressure that keeps the water moving through the siphon. The Catskill has 19 of these structures, constituting about 7% of the aqueduct's total length.
- ▶ To resist their substantial internal pressure, the Catskill siphon pipes were constructed of huge steel cylinders riveted together, lined with mortar on the inside, encased in concrete on the outside, and then covered with a protective layer of soil.
- ▶ Impressive as these structures are, they pale in comparison with the fourth channel configuration used in the Catskill Aqueduct: the **pressure tunnel**. There are seven of these, totaling 17 miles, or 18% of the aqueduct's total length. Their purpose is to carry water across particularly large valleys and deep rivers, locations where a surface-level siphon wouldn't be feasible.
- ▶ A pressure tunnel works in the same way as an inverted siphon. The only difference between them is that the pressure tunnel is bored through bedrock, while the inverted siphon is placed on the ground surface of a valley.

TERMS

arch: A structural element that carries load primarily in compression and must have its outer ends laterally restrained in order to carry load successfully.

arch dam: A dam that resists hydrostatic pressure through the action of an arch that transmits load in compression to the walls of the valley in which it is constructed.

dam: An engineered structure designed to impound water, generally by blocking the flow of a natural watercourse. A dam creates a reservoir and must control the release of water from that reservoir. Dams are used for water supply, irrigation, flood control, and the generation of hydroelectric power.

earth dam: A gravity dam that uses soil as its primary fill material.

grade tunnel: An aqueduct tunnel that carries the channel through a mountain while maintaining a constant gradient.

gradient: The slope of a surface, typically measured as a ratio of vertical to horizontal distance and expressed as a percentage. Also called a **grade**.

gravity dam: A dam that attains its structural stability from its mass, rather than from arch action.

hydroelectric power: Electric power produced by water flowing through a turbine. The source of energy for hydroelectric power is the potential energy stored in water contained at a relatively high elevation behind a dam.

inverted siphon: A type of aqueduct channel in which the water flows through a pipe under pressure from a higher to a lower reservoir. In an inverted siphon, much of the channel is typically below the elevation of the lower reservoir.

open-channel flow: In hydraulics, a category of flow in which the conduit is partially full and the upper surface of the liquid is at atmospheric pressure.

outlet works: A conduit and associated equipment (gates, valves, etc.) that is used to control the release of water from a reservoir through a dam.

pipe flow: In hydraulics, a category of flow in which the liquid completely fills the conduit and flows under pressure.

pressure tunnel: A type of aqueduct channel in which the water flows through a deep underground channel that passes beneath an obstacle. A pressure tunnel is a form of inverted siphon.

rock-fill dam: A gravity dam that uses rock as its primary fill material.

water distribution: The delivery of treated water to consumers.

READINGS

Dewberry, ed., *Land Development Handbook*, chapters 26 and 28.

Galusha, *Liquid Assets*.

Hayes, *Infrastructure*, chapter 2.

QUESTIONS

- 1 If you receive your water from a municipal water supply system, use your water bill to calculate your average daily water consumption. How does your usage compare with the standard planning figure of 150 gallons per person per day?
- 2 Why are earth dams preferable to concrete dams for most municipal water supply systems?

Water Treatment and Distribution

Regardless of whether water has been delivered by an aqueduct, pumped from a well, or drawn from a nearby lake, it is raw water—it isn't ready for human consumption yet. Most raw water, particularly surface water, is loaded with contaminants, some of which can be hazardous to human health. Thus, municipal water supply systems require some level of treatment. In this lecture, you will learn about water treatment. While the primary focus will be on your local water treatment plant, it's important to recognize that some aspects of water purification begin before the raw water reaches this facility.

Raw Water

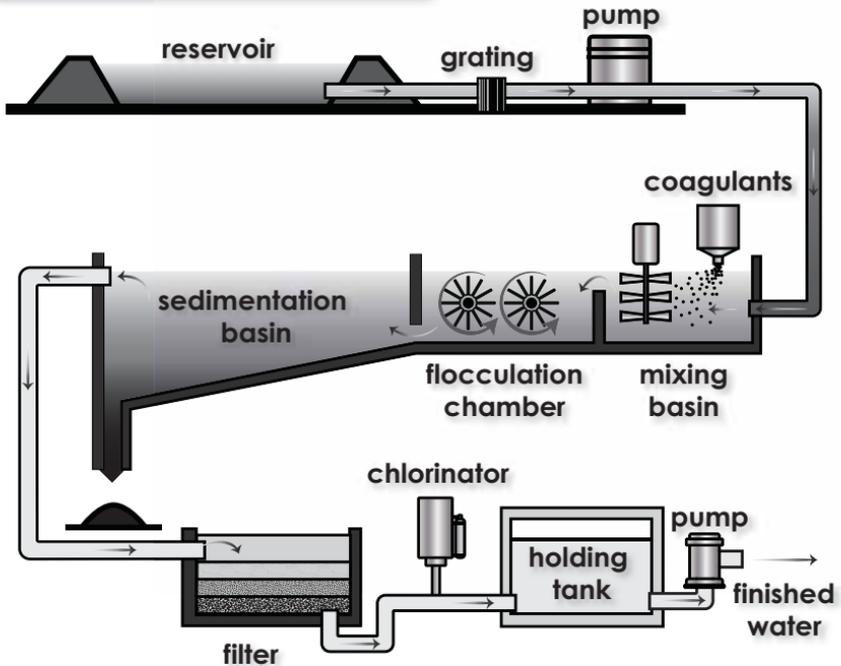
- ▶ When water is impounded in a reservoir or lake, a number of water-quality problems may result. The first is the growth of algae and aquatic plants, which feed on fertilizers that are washed into the reservoir by storm runoff. Some algae and plants are toxic, but most are just a nuisance; they give the water an unpleasant taste and may foul pipelines and pumps.
- ▶ The best defense against algae is to deny it food by using storm runoff management to keep fertilizers out of the reservoir. If this approach isn't feasible, then the algae can be removed mechanically, using a device like an algae harvester, or they can be killed by treating the water with the chemical **copper sulfate**.
- ▶ But this chemical can be toxic to fish if used in excessively high concentrations, and it can exacerbate another problem that's often encountered in reservoir management: **anoxia**, the depletion of dissolved oxygen near the bottom of a body of water.

- ▶ Anoxia can occur naturally, as a result of inadequate water circulation, but if copper sulfate treatments kill too much algae too quickly, the loss of dissolved oxygen will be greatly accelerated by the oxidation of all the rotting organic material. Anoxia kills fish; they suffocate for lack of oxygen. It also encourages the growth of **anaerobic** bacteria, which give the water a foul smell.
- ▶ The cure for anoxia is **aeration**, which restores oxygen to the water. Environmental engineers use an effective technique: An air **compressor** on shore forces air through a pipe to a fixture located on the bottom of the reservoir. This device sends a continuous stream of bubbles up to the surface. The bubbles add oxygen to the water in the immediate vicinity of the aerator, but, more importantly, the upward stream sets up a circulation pattern that draws the oxygen-starved water up to the surface, where it can be replenished naturally.

The Water Treatment Plant

- ▶ The water treatment plant uses an integrated series of mechanical and chemical processes to perform three basic functions: **clarification**, **filtration**, and **disinfection**.

water treatment process



- ▶ As **raw water** is pumped from a lake, river, or receiving reservoir into the treatment plant, it passes through a series of progressively finer gratings and screens to remove trash, leaves, aquatic weeds, and critters.

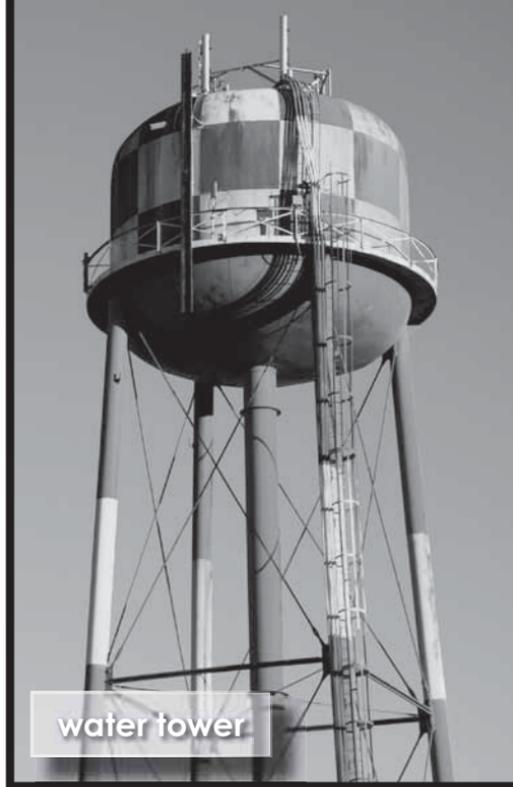
- ▶ The water then enters a mixing basin, where a chemical **coagulant** is added and vigorously mixed. The purpose of the coagulant is to neutralize the electrical charges that cause suspended particles in the water to repel each other. The coagulant causes these particles to cling together, forming progressively larger clumps of impurities, called flocs. This process, called **flocculation**, concludes when the flocs become so heavy that they settle to the bottom of the basin.
- ▶ The accumulated sludge is periodically raked out, dried, and disposed of in a landfill. This first phase of the water treatment process is called clarification.
- ▶ Back at the treatment plant, the clarified water is pumped through a filter, typically composed of horizontal layers of gravel, sand, and anthracite **coal**. As the water passes through this filter, any particulate matter that didn't settle out during clarification is captured in the tiny voids between the sand grains. The coal serves as a source of carbon, which is particularly effective at capturing volatile organic chemicals and removing them from the water.
- ▶ With filtration complete, the water is disinfected—usually by mixing in a small quantity of dissolved chlorine, which kills any bacteria or viruses that might have survived clarification and filtration. Alternative methods of disinfection include exposing the water to ultraviolet light or ozone. Both of these methods are also effective at killing pathogens.
- ▶ Finally, the purified water passes into a holding tank, which gives the chlorine more time for disinfection, while also providing a reservoir for smoothing out fluctuations in demand. At this point, the water treatment process is complete, and the finished water enters the local distribution system.
- ▶ **Desalination** is a different type of water treatment process that converts seawater into drinking water for roughly 300 million people around the globe. This process has been around for a long time, but it's undergoing a major surge in popularity today, as a result of recent technological advances.

- ▶ The most important of these is a technology called **reverse osmosis**, which removes salt from seawater by forcing it through a membrane under pressure. These kinds of improved technologies have cut the cost of desalination in half over the past decade; nonetheless, desalination is still significantly more energy intensive (and therefore more expensive) than treating surface water or groundwater. And its economic viability is further constrained by the fact that seawater is always obtained at a low elevation—a seacoast—and thus must be pumped to a higher elevation and transported inland for consumption.
- ▶ Nonetheless, there are places in the world, such as Israel, where desalinated seawater is practically the only reliable water source available to entire populations. And as the technology continues to improve, we can expect to see more of this trend.

The Water Distribution Network

- ▶ The single most important characteristic of our local water distribution system—the characteristic that distinguishes it from both storm drainage and **sanitary sewer** systems—is that water distribution operates under pressure. Using hydraulics terminology, water distribution is based on pipe-flow rather than open-channel-flow principles.
- ▶ The pressure that makes a pipe-flow system work can be provided by gravity, but only in the rare circumstance where the water treatment facility is located at a higher elevation than every consumer served by the distribution system. In all other cases, the pressure must be supplied by one or more pumping stations that use one or more electric pumps to propel water from the treatment plant into the distribution network.
- ▶ The network is composed of large pipes, called **water mains**; smaller pipes, called **water service lines**; connectors; valves; fire hydrants; and an **intermediate storage facility**—typically a water tower, located on high ground, close to the population it serves—which greatly enhances both the efficiency and robustness of the system.

- ▶ This system is highly efficient because, without the water tower, a much larger pump—or perhaps several larger pumps—would be required to meet the demand during peak times. The system is robust because the tower will continue to supply water even if a power failure shuts down the electric pumps.
- ▶ Water mains are large pipes that are sometimes made of PVC plastic or steel but most often made of iron, which resists corrosion better than steel. These pipes are almost always located underground to protect them against freezing.



- ▶ Water mains generally follow public streets, because the municipality already owns the right-of-way there. Storm drains and sanitary sewers also follow the public streets, and because all three of these systems have distinctly different points of origin and distinctly different destinations, there's great potential for them to interfere with each other.
- ▶ When such conflicts occur, it's always the water main that dips beneath or bends around the other two systems. Storm drains and sanitary sewers operate under the principle of open-channel flow, so their channels must be constructed on a steady downhill gradient—without exception. Conversely, the water distribution system is the only one of the three that operates under pressure; thus, water mains can change gradient and direction with no problem, even flowing uphill when necessary to avoid a conflict with a storm drain or sewer.

- ▶ For this same reason, water mains typically don't use the riverlike topology used in storm drainage systems, with many small tributaries flowing into progressively smaller numbers of larger streams. Ideally, water mains are arranged in interconnected loops, which can also be visualized as a grid pattern.
- ▶ If the water main fails at a particular location, it's easy to isolate a small section of the main and make the necessary repairs, disrupting water supply to only a limited number of homes. Thanks to the looped configuration, water can flow through a main in either direction, and because the system is pressurized, the water will always find its own path around a closed segment. With a branched topology, a failure in one location would cause many more homes to lose their water supply until the repair was completed.
- ▶ The greatest challenge in designing a water distribution network is maintaining an appropriate level of pressure throughout the system. Most systems operate with water mains pressurized between 40 and 60 pounds per square inch. If the region served by the water distribution system has large changes in elevation, the system must typically be divided into several pressure zones, interconnected with special pressure-regulating valves.

The Private Component

- ▶ Beneath the street in front of your house, a copper or plastic service line branches off from the main and conveys a stream of **potable water** into your plumbing system. At your property line is a **curb valve**, which can be used to cut off your entire water supply from outside the home. Beyond the curb valve, the service line enters your home through a hole in the foundation wall or floor slab. Just inside is your water meter and an interior shutoff valve. This is the one you'll want to close to keep your basement from flooding when a pipe bursts.

- ▶ From here, a separate pipe branches off of the main service line to supply the hot-water heater. From this point forward, the hot and cold water lines run parallel to each other throughout the building, supplying sinks, tubs, and showers, while the cold water line also supplies toilets, exterior spigots, and perhaps an ice maker in your refrigerator.
- ▶ Throughout this network, whenever you open a faucet, turn on a shower, use a washing machine, or flush a toilet, water flows freely because of the combined effects of a distant pumping station and a water tower, which supply the pressure that makes this system work.
- ▶ But pressure is a double-edged sword. Water that's flowing through a pipe under pressure has considerable momentum. If the flow is shut off suddenly (by quickly closing a faucet, for example), the resulting shock—called **water hammer**—can damage pipe joints and fixtures. To prevent water hammer, water supply lines are fitted with air-filled expansion chambers, which effectively absorb the shock.

TERMS

aeration: The introduction of oxygen into water, for the purpose of reducing anoxia.

anaerobic: Occurring in the absence of oxygen.

anoxia: The depletion of dissolved oxygen near the bottom of a body of water.

clarification: In water treatment, the process of removing suspended particulate matter from raw water.

coagulant: A chemical substance used for clarification in water treatment. The coagulant causes suspended particles to cling together, resulting in clumps of impurities—called flocs—sinking to the bottom of the container.

coal: A black or brownish sedimentary rock, composed primarily of carbon, mixed with varying amounts of impurities—primarily hydrogen, sulfur, oxygen, and nitrogen.

compressor: A mechanical device that increases the pressure of a fluid while reducing its volume.

copper sulfate: A chemical used to kill algae contamination in a water supply reservoir.

curb valve: An exterior valve that can be used to cut off the water supply to an individual building.

desalination: The process of converting seawater into potable water by removing salt, typically through reverse osmosis.

disinfection: In water treatment, the use of chlorine, ultraviolet light, or ozone to kill bacteria and viruses in raw water.

filtration: In water treatment, the use of a filter composed of horizontal layers of gravel, sand, and anthracite coal to remove particulate matter and volatile organic chemicals from raw water.

flocculation: In water treatment, the process by which suspended particles clump together under the action of a chemical coagulant. Each resulting clump of particulate matter is called a floc.

intermediate storage facility: A tank for temporary water storage in a water distribution system.

potable water: Water that is safe for drinking.

raw water: Untreated water obtained from a natural source.

reverse osmosis: The process of removing salt from seawater by forcing the water through a membrane under high pressure.

sanitary sewer: A municipal wastewater disposal system consisting of progressively larger pipes called branches, trunks, and interceptors.

water hammer: A shock that occurs when the flow of water in a pipe is shut off suddenly.

water main: A large pipe that serves as a principal element of a water distribution system.

water service line: A pipe that branches off of a water main to supply water to an individual building.

READINGS

Dewberry, ed., *Land Development Handbook*, chapters 26 and 28.

Hayes, *Infrastructure*, chapter 2.

Nazaroff and Alvarez-Cohen, *Environmental Engineering Science*, chapters 2 and 6.

Wing, *The Visual Handbook of Building and Remodeling*, chapter 11.

QUESTIONS

- 1 Can you find the water supply shutoff valve in your home? (You should know where this valve is located so that you can shut off your water supply in case of emergency.)
- 2 Why is open-channel flow never used in a municipal water distribution system?

Wastewater Disposal and Treatment

This lecture is about sewage, focusing primarily on the centralized treatment facility but concluding with an overview of on-site septic systems. Your local sewage treatment plant takes sewage (or, more properly, wastewater)—a foul, unhealthy by-product of human existence—restores it to crystal clarity, and then returns it to nature without harming the environment. Our pungent exploration of wastewater disposal and treatment begins precisely where our exploration of water distribution left off: at a plumbing fixture in your home.

Wastewater Treatment Systems

- ▶ In general, a fixture is a device that draws clean water from the distribution system and discharges wastewater into the sewage system without allowing any flow in the opposite direction. The most common residential plumbing fixtures—toilets, showers, bathtubs, sinks, and washing machines—all share this fundamental characteristic: a distinct break between clean water flowing in and dirty water flowing out, with no opportunity for the bad to contaminate the good.
- ▶ The purpose of your household plumbing system is to capture the wastewater discharge from all of these fixtures and combine it into a single stream for disposal. This stream is composed of more than 99.9% water.
- ▶ The remaining 0.1%—somewhat euphemistically called “suspended and dissolved solids”—is a complex and potentially unhealthy mixture that includes dissolved organic material, which originates from both human waste and food; suspended inorganic particles, or grit; rags, paper, plastic, and similar materials that somehow get flushed down toilets; and a high concentration of enteric microorganisms, bacteria



sewage treatment facility

that originate in our intestines and may include some pathogenic, or disease-causing, forms. This is the stuff that all wastewater treatment systems are designed to remove.

- ▶ In the United States, about 75% of residences send their wastewater through a sanitary sewer network to a centralized sewage treatment facility, which cleans the water and discharges it into a natural watercourse. The remaining 25% of residences, primarily in rural and suburban areas, use **on-site septic systems**.
- ▶ Regardless of configuration, wastewater systems operate primarily by gravity-driven flow. Thus, with only a few exceptions, every conduit in the system must be placed at a carefully controlled downhill slope, or gradient, to ensure the steady movement of wastewater through the system. That's why you're quite likely to find your wastewater treatment plant at the lowest point in town.

Your Plumbing System

- ▶ The central spine of your residential wastewater system is a large-diameter vertical pipe called the **soil stack**, extending from above your roof (where it serves as a vent) straight down to your basement floor or ground-level slab, where it connects to a gently sloped underground pipe, called a **lateral**, that feeds into the municipal sewer system or your on-site septic tank.
- ▶ In residential plumbing, most wastewater pipes originate at fixtures and end at the soil stack. Building codes also allow fixtures other than toilets to empty into a smaller vertical drain pipe called a secondary stack.
- ▶ In either configuration, every pipe running from a fixture to a stack must be mounted on a gradual downhill gradient along its entire length, with one important exception—the U-shaped bend located directly beneath each drain. It's called a trap, and it's one of the most important features of your plumbing system.
- ▶ Although configurations vary, there's a trap directly beneath every drain in your home. Because of its shape, the trap is always filled with water, and this water forms a plug that prevents noxious gases from reentering your home from the sanitary sewer.
- ▶ Every wastewater line in your plumbing system has a vertical pipe called a vent, and each vent either runs up through the roof or connects with the upper end of the soil stack, which also extends through the roof. The purpose of this vent is to ensure that atmospheric pressure is maintained on either side of a trap. Without it, wastewater rushing down the drainpipe can create a partial vacuum, and this vacuum can suck the water out of the trap, breaking its airtight seal.
- ▶ As wastewater flows from the soil stack, it enters either a municipal sanitary sewer system or an on-site septic system. The sanitary sewer begins with a lateral, the underground pipe that runs from your soil stack to the street, where it connects to a larger pipe called a branch. Branches feed into progressively larger pipes—typically called trunks

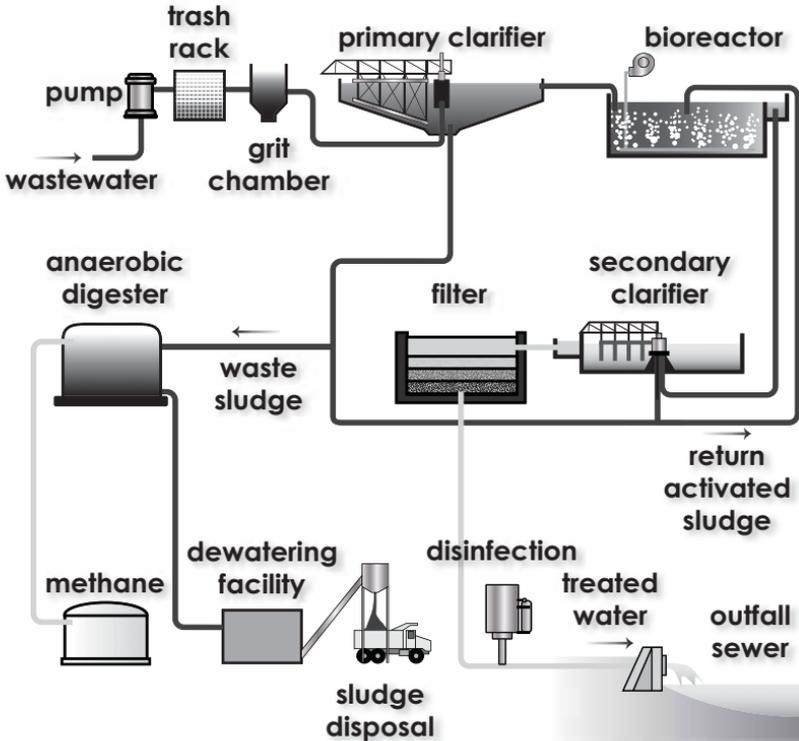
and interceptors—in a treelike topology very similar to the one in storm drainage systems.

- ▶ Sanitary sewer lines usually follow public streets, and they always follow a steady downhill gradient, unless the topography prevents it. The slope of a sewer pipe is designed such that the flow is fast enough to keep those nasty suspended solids moving, but not so fast that this gritty liquid erodes the inside of the pipe.
- ▶ In cases where topography prevents a continuous downhill gradient, a **sewage lift station** is installed to pump the wastewater stream to a higher elevation, at which point it resumes its gravity-driven downhill flow.
- ▶ Sewer pipes are often the deepest buried of all utilities. Manhole covers provide access to the sewer line for maintenance and repair. Manholes are typically located where the underlying pipe intersects with another sewer line, or changes direction or slope.

The Wastewater Treatment Plant

- ▶ A wastewater plant has essentially the same purpose as a water treatment facility and actually uses many of the same types of equipment. But where water purification relies primarily on mechanical and chemical processes, wastewater treatment is also heavily dependent on biological processes.
- ▶ Treatment begins as the wastewater stream enters through a series of trash racks, which are metal grills that filter out large pieces of debris and foreign objects. From here, the flow enters a grit chamber, which is designed to settle out the larger suspended particles (such as sand, coffee grounds, and watermelon seeds) to keep them from damaging pumps and other equipment at later stages of treatment.
- ▶ Next, the wastewater enters a sedimentation tank, also called a primary clarifier. The stream is pumped in from the center and then flows very slowly toward the outer perimeter. Along the way, floatable contaminants

wastewater treatment process



rise to the surface and form a greasy scum that's removed by a skimmer mounted on a rotating platform. Simultaneously, heavier material settles to the bottom as sludge and is raked into a sump at the center of the tank and then pumped out.

- ▶ After about two hours in the clarifier, the wastewater has shed most of its floatable scum and suspended solids; it's decanted over the rim of the tank and collected in a trough below. At this point, the water is said to have undergone **primary treatment**.



sedimentation tanks

- ▶ The fundamental challenge in **secondary treatment**—required by federal law to meet modern water quality standards—is a phenomenon called **biochemical oxygen demand (BOD)**. Water naturally contains dissolved oxygen, which it acquires through contact with the air and from the photosynthesis of algae and aquatic plants. Dissolved oxygen is critical for the health of an aquatic ecosystem, because fish and other aquatic animals need it to breathe.
- ▶ Most water also contains some organic compounds. Aquatic bacteria and other microorganisms consume these organic compounds as food. This decomposition of organic compounds involves oxidation, a chemical process that consumes dissolved oxygen in the water. And within a body of water, the population of these microorganisms tends to increase in proportion to the availability of food.

- ▶ Wastewater is loaded with organic material (primarily from human waste), even after primary treatment. Thus, we say that wastewater has a very high BOD—biochemical oxygen demand—because those organic compounds are present in abnormally high concentrations, and the resulting large population of hungry microorganisms severely depletes the quantity of dissolved oxygen in the water.
- ▶ The most common technology for reducing BOD to environmentally safe levels is the **activated sludge** process. In this process, the wastewater stream is directed into a series of deep vats called **bioreactors**, where it's combined with carefully managed populations of bacteria, protozoa, worms, and microscopic animals called rotifers. These microorganisms rapidly consume the organic compounds in the water and thus reduce its BOD, under controlled conditions.
- ▶ This process requires lots of oxygen, so activated sludge reactors are always vigorously aerated, either by mechanical agitators or by streams of air pumped up from the bottom of each reactor. In either case, the activated sludge reactors are filled with bubbling, roiling, frothing brown liquid. Environmental engineers call this foul stuff mixed liquor. Despite its appearance, it is actually being purified by an army of bacteria and bugs conscripted especially for this purpose.
- ▶ Having introduced all these critters into the effluent stream, we need to get them back out. Thus, the stream is now transmitted into a secondary clarifier tank, where the mixed liquor is still, the microorganisms settle to the bottom, and a portion of this activated sludge is returned to the reactor to reseed the biological treatment process.
- ▶ The clarified water is drawn off. It's sometimes passed through a filter to remove any particulate matter that didn't settle out in the clarifier, and then it's disinfected with a final dose of chlorine to kill any remaining bacteria.
- ▶ The water is now clean and safe for discharge into the local stream, through a conduit called an **outfall sewer**. However, all of that sludge collected from the clarifiers and filters still needs to be treated. This is

accomplished through another biological process called **anaerobic digestion**, bacterial decomposition in the absence of oxygen. The products of anaerobic digestion are **methane** gas (which can be collected and burned as fuel) and a solid residue that can be used as fertilizer after dewatering.

The On-Site Septic System

- ▶ The typical wastewater treatment plant is a major industrial facility that uses complex physical, chemical, and biological processes to treat millions of gallons of sewage per day. At the opposite end of the technological spectrum is the on-site septic system that is used by about a quarter of all residences in the United States.
- ▶ An on-site system consists of two major components: a **septic tank** and a **drain field**. The typical septic tank is a large, closed watertight concrete container with a capacity of 1000 to 2000 gallons, installed with its top just below ground level, with an inlet from your sewage lateral at one end and an outlet to the drain field at the other.
- ▶ The most impressive characteristic of this system is that it replicates all of the major processes in the wastewater treatment facility—sedimentation, floatation, anaerobic digestion of solids, filtration, and activated sludge treatment—with no moving parts and with human intervention required only to pump the sludge out of the septic tank every few years. The downside is that it requires a fairly large piece of land, and it only works well in soils with just the right degree of permeability. These systems are tightly regulated by states and municipalities.



TERMS

activated sludge: A process used in the secondary treatment of sewage. Wastewater is combined with carefully managed populations of bacteria, protozoa, worms, and microscopic animals that consume the organic compounds in the water and thus reduce its biochemical oxygen demand (BOD).

anaerobic digestion: A process of bacterial decomposition in the absence of oxygen that is used for the treatment of sludge at a sewage treatment facility.

biochemical oxygen demand (BOD): The depletion of dissolved oxygen in water as aquatic bacteria and other microorganisms consume organic compounds as food. Wastewater has a high BOD, which must be reduced through secondary treatment.

bioreactor: A vessel in which the activated sludge process is implemented for secondary sewage treatment.

drain field: A component of an on-site septic system that receives wastewater from a septic tank and discharges it into the surrounding soil. A series of perforated pipes surrounded by a bed of crushed stone and covered with soil, the drain field promotes filtration and biological treatment of wastewater flowing through the system.

lateral: A pipe that carries wastewater from a soil stack inside a building to a sewer line or on-site septic system.

methane: A hydrocarbon with chemical formula CH_4 . Methane is the principal component of natural gas and is also produced by the decomposition of organic material.

on-site septic system: A wastewater treatment system for a single residence. A typical on-site septic system consists of a septic tank and a drain field.

outfall sewer: A pipe that discharges treated wastewater into a natural watercourse.

primary treatment: In sewage treatment, the removal of floatable contaminants and sludge from wastewater in a sedimentation tank (also called a primary clarifier).

sewage lift station: A pump used to lift the flow of sewage to a higher elevation in situations where continuous downhill flow are not feasible.

secondary treatment: In sewage treatment, the reduction of biochemical oxygen demand (BOD) in wastewater through the use of natural biological processes.

septic tank: A closed, watertight container that is used to remove suspended solids from wastewater in an on-site septic system.

soil stack: A large vertical pipe that collects all wastewater from a plumbing system and delivers it to the municipal sewage system or on-site septic system.

READINGS

Dewberry, ed., *Land Development Handbook*, chapters 25 and 27.

Hayes, *Infrastructure*, chapter 2.

Nazaroff and Alvarez-Cohen, *Environmental Engineering Science*, chapter 6.

Wing, *The Visual Handbook of Building and Remodeling*, chapter 11.

QUESTIONS

- 1 Toilets manufactured before 1982 in the United States use 5 to 7 gallons of water per flush. Today, most toilets are designed to use only 1.6 gallons per flush. What are the implications of this change for water supply, as well as for wastewater treatment?
- 2 Estimate how much wastewater you discharge from your home every day.

Fossil Fuels: Coal, Oil, and Natural Gas

LECTURE 10

Fossil fuels—coal, oil, and natural gas—are the lifeblood of our industrial economy and are integral to everyday engineering. Their influences are observed throughout this course, from the use of vinyl siding and asphalt shingles in residential construction to electric power generation, home heating systems, the internal combustion engine, highways, railroads, and even landfills. To understand these systems, you need to know something about the technologies used to extract fossil fuels from the Earth's crust. In this lecture, you will explore these extractive technologies as fascinating engineered systems.

Coal

- ▶ A century ago, coal was used to heat homes and power trains and ships, the principal means of long-distance transportation. The infrastructure of coal distribution—coal yards, coal wagons, and coal bins—were as ubiquitous as the infrastructure of electrical power distribution is today.
- ▶ Today, nearly all of the coal mined in the United States is shipped directly to power plants and heavy industries, such as steel manufacturing. So, we hardly ever see the stuff, even though we feel its influence every day.
- ▶ Coal is a black or brownish sedimentary rock, composed primarily of carbon, mixed with varying amounts of impurities—primarily hydrogen, sulfur, oxygen, and nitrogen. The coal deposits that are mined today originated in the distant past, when layers of dead vegetation accumulated on swampy ground and then were covered with layers of soil and subjected to progressively greater pressure and heat. As a result of this formation process, coal is typically found in more-or-less horizontal strata called coal beds or seams, with the higher-quality types found at greater depths.



coal

- ▶ Coal is extracted from deposits in the United States by two principal methods: **underground mining** and surface mining. Underground mining involves the excavation of tunnels and shafts to access coal beds deep underground. It was the world's most common form of mining for millennia, until the availability of large-scale earthmoving equipment made surface mining more economical in most circumstances. Today, underground mining is used primarily for extracting coal that's too deep to be reached by other means.
- ▶ The raw coal extracted from a mine requires considerable processing before it can be shipped to customers. This is accomplished at an on-site coal processing plant that washes the coal, crushes it into chunks of graded sizes, and separates unwanted soil and rock.

- ▶ Mine safety has improved considerably in recent years, but underground mining remains a very dangerous business. Safety is one reason why, today, most of America's coal comes from surface mining, primarily in a swath of Western states from Wyoming and Montana down to Arizona and New Mexico. The principal method for extracting this coal is opencast mining, a term coined in the 1970s after its former name, strip mining, became virtually synonymous with environmental degradation.
- ▶ Along with coal's contributions to power generation, we must also recognize its serious environmental impacts. The effects of coal mining can include destruction of wildlife habitats, altered landforms, dust pollution, increased erosion, decreased soil fertility, depleted groundwater, methane gas emissions, sinkholes, and underground fires.
- ▶ In the past few decades, federal and state laws have eliminated the worst abuses through stringent requirements for permitting, inspections, and reclamation of mined-out lands. Yet the adverse effects can't be eliminated entirely, so they must be considered in our ongoing struggle to find the right balance between environmental protection and our ever-increasing appetite for energy.

Oil

- ▶ The world consumes more than 90 million barrels of oil every day. And even though oil fuels only 1% of U.S. electric power generation, it constitutes 40% of our total energy consumption. **Petroleum** products power our automobiles and aircraft, heat our homes, cook our meals, and lubricate our machines. They serve as a base for countless industrial chemicals and plastics.
- ▶ Complain as we might about oil as a nonrenewable resource, a source of pollution and greenhouse gases, and a source of international conflict, we depend on this stuff for our standard of living and will continue to depend on it for some time to come.

- ▶ Petroleum is a naturally occurring stew of **hydrocarbons**, organic compounds consisting entirely of hydrogen and carbon atoms. A major component of the unrefined crude oil we pump from the ground is a family of hydrocarbon molecules called **alkanes**. An alkane is a chain of carbon atoms, each bonded to two hydrogen atoms—except at the ends of the chain, where each carbon is bonded to three hydrogens.
- ▶ Petroleum originated as marine microorganisms—primarily plankton and algae—that accumulated on the bottom of the sea 10 to 600 million years ago. Over time, these organisms decomposed into compounds of carbon and hydrogen, which were embedded within sedimentary layers that eventually hardened into fine-grained **shale**, called **source rock**.
- ▶ As the source rock experienced progressively greater heat and pressure, the organic material was distilled into petroleum and natural gas, which eventually accumulated in more porous strata of limestone and sandstone, called **reservoir rock**. Here it was retained, as geological movements of the Earth’s crust sandwiched the reservoir rock between layers of impermeable caprock, such as granite and marble.
- ▶ Armed with a deep understanding of this formation process, geologists use a variety of technologies to identify possible deposits of oil and natural gas deep underground. These include satellite imagery, seismology, gravity meters, magnetometers, and electronic sniffers.
- ▶ Once a deposit of oil has been identified, the process of extracting it begins with a **drilling rig**. At its heart is the **drill string**, a series of hollow pipes connected with threaded couplers. At the bottom of the string is the bit, which excavates the borehole as it rotates. Immediately above the bit are several heavy sections of pipe called **drill collars**, which fit over the drill string and provide the weight needed to drive the bit downward through solid rock.
- ▶ The drilling process relies on a specialized lubricant called **drilling mud**, a mixture of water, bentonite clay, and a few other ingredients. During drilling, this substance is pumped downward through the hollow drill string.

drilling rig



- ▶ Drilling continues until the bit reaches a depth just above the expected location of the oil deposit. Then, the drill string is withdrawn, and a steel pipe called the **well casing** is inserted into the borehole to keep it from collapsing inward. Once in place, the casing is supported and sealed by pumping cement **slurry**, or mortar, down through the casing, followed by a plug, followed by drilling mud.
- ▶ After some additional drilling to reach the oil deposit, the **well** is prepared for operation. Explosive charges are lowered to the bottom of the borehole and detonated to create perforations in the bottom of the casing. A small-diameter pipe is then lowered into the casing and sealed into position. This pipe creates a conduit through which the oil can flow upward.
- ▶ Underground oil resides within tiny pores and fissures in a stratum of limestone, sandstone, or shale. To get this oil flowing into the well, additional measures usually must be taken. If the stratum is sandstone,

oil refinery



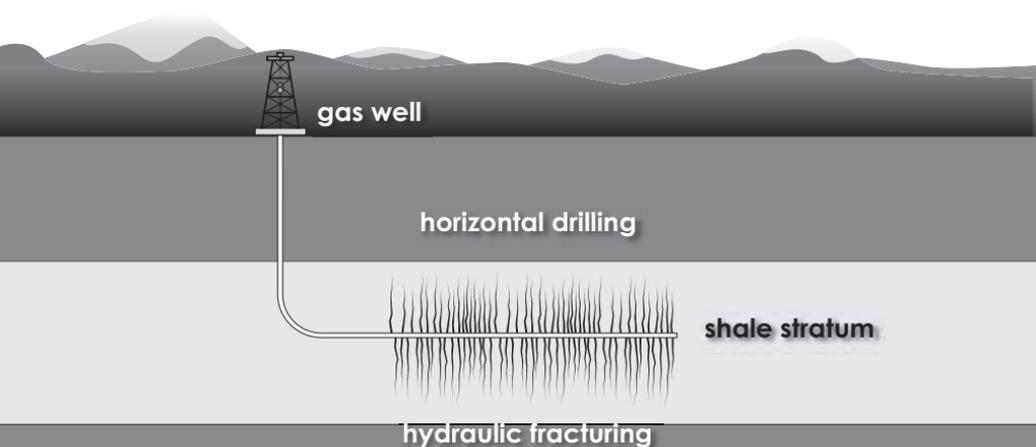
water mixed with a **proppant** (typically sand, walnut shells, or aluminum pellets) is pumped into the well at very high pressure. The high-pressure fluid fractures the rock, and the proppant particles hold these cracks open so that the oil can flow through them. This process—called **hydraulic fracturing**, or fracking—is also used in the extraction of natural gas.

- ▶ At this point, drilling is complete. The drilling rig is disassembled and hauled away, and production equipment is installed to extract oil from the well.
- ▶ Much of our petroleum originates with offshore drilling. The offshore-drilling process is fundamentally the same as for land-based drilling, except its execution is far more complex and much riskier.
- ▶ Of course, the stuff that flows from any wellhead—onshore or off—isn't quite ready for your car's gas tank. This unrefined crude is a mixture of oil, natural gas, water, and various impurities. Immediately after extraction, these components undergo preliminary separation at a processing facility, typically located right in the oil field. Only after this processing does the stuff actually qualify as crude oil.
- ▶ Bulk crude is then transported to a refinery over water by tanker ships and over land by pipeline. The oil refinery's principal function is to separate crude oil into its constituent alkane hydrocarbons, through a continuous process called **fractionating**. The typical refinery incorporates many other processes, such as removing impurities.

Natural Gas

- ▶ The natural gas we use for heating, cooking, and generating electricity is methane, the lightest of the alkane hydrocarbons. In the United States, about one-quarter of natural gas production is **associated gas**, meaning that it's found within, and extracted from, petroleum deposits. In these deposits, methane is often dissolved in the oil and kept in solution by the very high pressure underground, but as the mixture is brought to atmospheric pressure at the surface, the methane comes out of solution naturally.

- ▶ Before the development of gas pipelines in the 1950s, this associated methane was seen as an unwanted by-product and was burned off in the oil field. Today, it's usually captured and piped to a gas plant for processing and sale.
- ▶ The remainder of U.S. natural gas production is **nonassociated gas**—found in gas fields and coal beds separate from oil deposits—but extracted using essentially the same drilling process that is used for oil.
- ▶ Even though natural gas is mostly methane, it still requires refinement at a natural gas processing plant to remove water vapor and impurities and to separate and capture small amounts of other gaseous hydrocarbons. The finished product is then transported to customers through a network of pipelines, aided and controlled by compressors and gates.
- ▶ Since 2000, there's been a revolution in natural gas production, resulting from the large-scale exploitation of shale gas, particularly in the United States and Canada. There are large reserves of shale gas around the world, but until recently, they couldn't be exploited economically, because shale is too impermeable—the gas trapped within it couldn't be extracted.
- ▶ The recent boom has been enabled by two important technological developments. The first is horizontal drilling, which is used to maximize the surface area of the borehole within a shale stratum. The second is



hydraulic fracturing, or fracking, the process of injecting a mixture of water and chemical additives at high pressure down into the borehole to create fractures through which the gas can flow.

- ▶ Today, fracking has completely changed the economics of energy in the countries where it's being used. Because fracking has increased our technically recoverable deposits by about 50%, natural gas is now the fastest-growing contributor to the U.S. energy supply. Prices have dropped significantly, as has our dependence on foreign sources of fossil fuel. However, fracking is highly controversial, largely because of its adverse environmental impacts—the extent of which aren't yet fully understood.

TERMS

alkane: A chemical compound consisting of a chain of carbon and hydrogen atoms with the general chemical formula C_nH_{2n+2} , where n is the number of carbon atoms. Alkanes are hydrocarbons that constitute a major component of unrefined crude oil.

associated gas: Natural gas that is found within, and extracted from, underground petroleum deposits.

drill collar: In an oil or natural gas drilling rig, a heavy section of pipe located at the bottom of the drill string and immediately above the bit. Drill collars provide the weight needed to drive the drill bit downward through solid rock.

drill string: A series of hollow pipes connected together with threaded couplers that is used to drill the borehole for an oil or natural gas well.

drilling mud: In an oil or natural gas drilling rig, a mixture of water and bentonite clay that is used to lubricate the drilling bit and to carry the rock cutting back up to the surface.

drilling rig: A mechanical system used to drill deep into the Earth's crust to extract petroleum and natural gas.

fractionating: An industrial process by which crude oil is separated into its constituent hydrocarbons.

hydraulic fracturing: The process of using a high-pressure fluid to create fractures in underground rock to facilitate the extraction of oil or natural gas. Fracturing fluid contains proppants, which hold the fractures open after the fluid pressure has been reduced.

hydrocarbon: An organic chemical compound consisting of hydrogen and carbon atoms.

nonassociated gas: Natural gas that is found in gas fields and in coal beds separate from petroleum deposits.

petroleum: A naturally occurring mixture of hydrocarbons, organic compounds consisting entirely of hydrogen and carbon atoms.

proppant: In the process of hydraulic fracturing, a solid particulate material designed to keep a fracture open to facilitate the extraction of oil or natural gas.

reservoir rock: Porous underground strata of limestone and sandstone in which petroleum and natural gas accumulate.

shale: A fine-grained sedimentary rock that is formed primarily from clay minerals and quartz.

source rock: Fine-grained shale in which hydrocarbons form deep under the surface of the Earth.

underground mining: The excavation of tunnels and shafts to access mineral deposits deep under the surface of the Earth.

well: A shaft excavated from the ground surface into an aquifer for the purpose of obtaining groundwater.

well casing: A pipe inserted into an oil or natural gas well to prevent the walls of the borehole from collapsing.

READING

Hayes, *Infrastructure*, chapters 1 and 4.

QUESTIONS

- 1** What are the geopolitical implications of our heavy reliance on fossil fuels? What are the implications of the availability of ample coal reserves in the United States? What are the implications of the ongoing natural gas boom?
- 2** How does the issue of hydraulic fracturing exemplify the benefits and costs of technological development in our world? How does it exemplify the complex role of government in both promoting and controlling technological development?

Power Generation from Coal

Electricity is so deeply embedded in the fabric of modern civilization that we're seldom even aware that we're using it constantly—for illumination, heating and cooling our homes, preserving and cooking food, heating water, keeping time, washing clothes and dishes, entertaining ourselves, computing, driving, etc. Electricity is also essential for the other infrastructure systems covered in this course: telecommunications, transportation, water and wastewater treatment, oil and natural gas extraction, mining, and solid waste disposal. In a larger sense, our quality of life depends on that invisible source of energy, which you will learn about in this lecture.

Energy and Electrical Power

- ▶ There are many forms of energy.
 - Gravitational **potential energy** is the energy associated with the elevation of a mass.
 - **Kinetic energy** is the energy of motion.
 - **Electrical energy** is another form of potential energy that is associated with a difference in **voltage**, rather than a difference in elevation.
 - **Internal energy** is associated with the microscopic motions of the particles that constitute matter.
 - **Elastic energy** is associated with the deformation of a material.
 - **Chemical energy** is associated with the bonds between the atoms that constitute molecules.

- **Nuclear energy** is associated with the bonds between the particles that constitute the atomic nucleus.
- **Radiant energy** is associated with light and other forms of **electromagnetic radiation**.

► There are also two principal forms of energy transfer: heat and work. Heat is the thermal energy transferred from a region of higher temperature to a region of lower temperature. **Work** is the energy transferred through the movement of a force through a distance.

► At the most fundamental level, all of the different forms of energy are the same thing. As the law of conservation of energy tells us, energy can never be created or destroyed, but it can be transformed from one form into another. These transformations are vital, because they allow us to use energy from a given source in ways that wouldn't otherwise be possible. Our ability to engineer these transformations has made it possible for us to use electrical power as a sort of common currency for our energy-intensive world.

Force × Distance = Work

$$1 \text{ newton} \times 1 \text{ meter} / 1 \text{ second} =$$

$$1 \text{ newton-meter/second} =$$

$$1 \text{ watt}$$

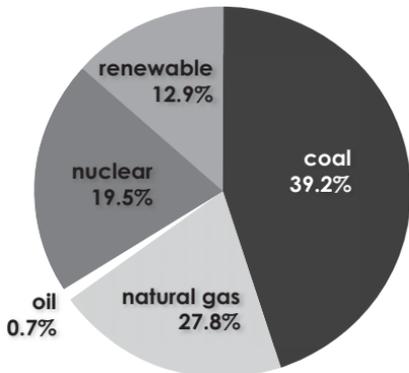
$$1 \text{ watt} \times 1 \text{ hour (3600 seconds)} =$$

$$1 \text{ watt-hour}$$

$$1 \text{ watt-hour} \times 1000 \text{ hours (3,600,000 lifts)} =$$

$$1 \text{ kilowatt-hour}$$

U.S. Energy Sources (2013)

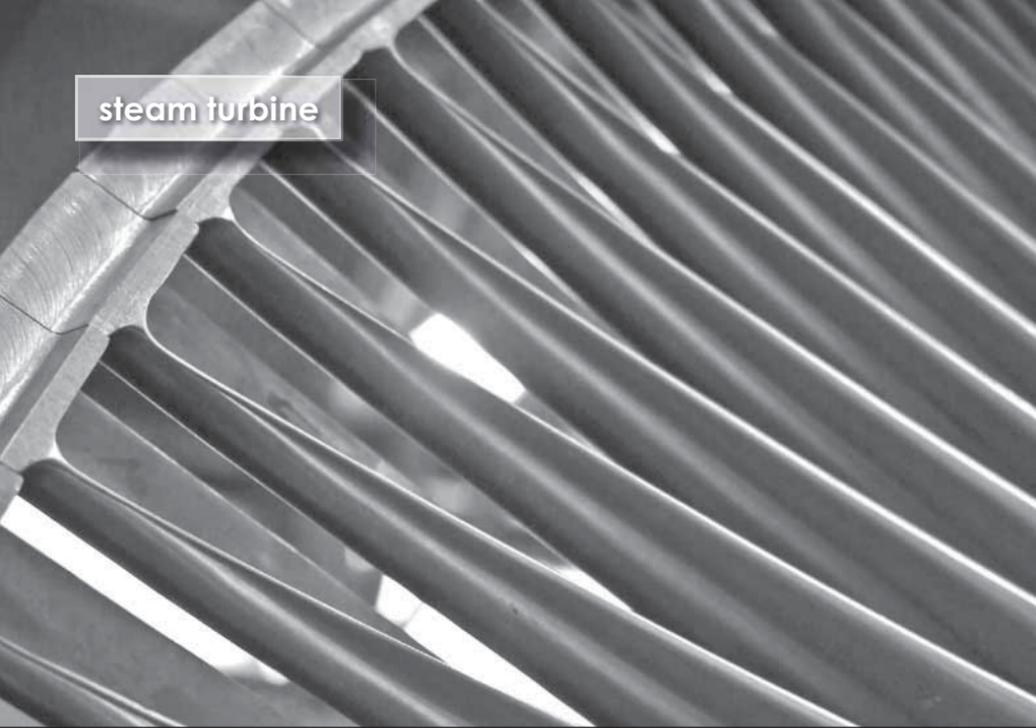


- ▶ The principal reason why electricity has become the common currency is that every significant natural source of energy available to us can be used to generate electrical power. As of 2013, about 67% of electrical power in the United States was generated by burning fossil fuels, about 20% was from **nuclear fission**, and about 13% was from renewable sources. Worldwide, the average percentages are similar, but there's significant variation from country to country.

Coal-Fired Power Plants

- ▶ The dominant source of electricity in the United States is coal-fired power plants. From a macro perspective, this technological system consists of three self-contained but closely interwoven subsystems: one for burning coal to produce a stream of hot flue gas, one for extracting heat from the flue gas to produce a continuous stream of high-pressure steam that drives a **turbine**; and one for transforming the turbine's shaft power into electrical power.
- ▶ Power generation begins with the delivery of massive amounts of coal to the plant by railroad or barge. A conveyor belt provides a continuous flow of coal from the storage yard into the plant. Inside, the coal enters a pulverizer, a rotating drum containing large steel balls that grind lumps of coal into a fine powder, which is then blown into the furnace with high-powered fans. Powdered coal burns more completely than larger pieces do; thus, pulverizing increases fuel efficiency while also reducing pollution.
- ▶ Inside the furnace, a 3000° fireball burns continuously, sending a stream of hot exhaust gases up into an arch-shaped flue. The purpose of the flue, and its associated equipment, is to extract every possible joule of heat from the exhaust gases before they're released to the atmosphere.
- ▶ This process of heat transfer begins with the boiler, consisting of tightly packed vertical steel tubes, called **risers**, integrated within the walls of the furnace itself. The risers are filled with water that **boils** and rises as it's heated by radiant energy from the flames. Each riser is part of a closed loop that allows for continuous circulation of this fluid.

- ▶ At the top of the loop is a device called a **steam drum**, which separates steam from the water. The separated steam is now piped to the next stage of the power-generation process, as part of a larger closed loop that constitutes the steam-power-generation cycle.
- ▶ Meanwhile, the separated water is circulated from the steam drum back to the bottom of the furnace, through pipes called **downcomers**, and then it's fed back into the risers, where the generation of steam continues.
- ▶ According to the laws of thermodynamics, the **efficiency** of a steam power cycle can be improved by increasing the temperature of the steam that's fed into the turbine. That's why the high-pressure steam emerging from the steam drum is now routed through a **superheater**, suspended within the hottest part of the arch-shaped flue. The superheater is really just a **heat exchanger**. Intensely hot flue gases flow across its coils, raising the temperature of the steam to about 1000°F, at which point it's ready for the turbine.
- ▶ A **steam turbine** is a mechanical device that converts the internal energy in steam into the kinetic energy of a rotating shaft. A heavy, airtight casing is needed to withstand the immense internal pressure the turbine experiences during use. Inside is a series of disks fixed rigidly to a shaft. Each disk, called a **rotor**, is composed of closely spaced angled blades.
- ▶ Alternating between the rotors, another set of similar disks, called **stators**, is rigidly fixed to the inside of the casing. The rotors turn with the turbine shaft; the stators stand still. Each pairing of one stator and one rotor is called a stage of the turbine.
- ▶ High-pressure steam enters at the narrow end of the turbine and moves toward the wider end, passing through successively larger stages, expanding as it goes. The process continues, stage by stage, until the steam is exhausted—at considerably lower pressure—from the far end of the turbine.



steam turbine

- ▶ Most power plants have three turbines driving the same shaft. The first is a high-pressure turbine that receives steam directly from the superheater and then sends it back to a **reheater**, located just beyond the superheater in the flue. The reheater transfers more waste heat from the flue gases into the steam, raising its temperature close to 1000°F, though not increasing its pressure.
- ▶ Next, the steam is piped, in succession, to an intermediate-pressure turbine and a low-pressure turbine, which extract even more energy and transmit it to the rotating shaft. The smaller high-pressure turbine does most of the heavy lifting.
- ▶ Steam leaving the low-pressure turbine enters a **condenser**, which changes the vapor back to liquid water for eventual return to the boiler. As the steam condenses, its pressure decreases considerably, creating a partial vacuum that helps pull the waste steam out of the turbine.

- ▶ Water collected from the bottom of the condenser will eventually be recirculated to the boiler to complete the so-called feedwater loop. But before this can happen, the feedwater is intensively purified to remove rust particles, dissolved minerals, dissolved oxygen, and acidity. The purified water is then pumped through a device called an economizer—which extracts even more waste heat from the flue gases—and then back into the steam drum, where it rejoins the flow of water through the downcomers to the boiler.
- ▶ A heat exchanger at the end of the flue is used to preheat the stream of fresh air that's mixed with pulverized coal and blown into the boiler at the beginning of this process. Finally, these exhaust gases are processed through a series of pollution-control devices and then released through the top of a smokestack into the atmosphere.
- ▶ Meanwhile, back in the power plant, the ultimate purpose of all these interwoven processes is finally realized: The turbine shaft turns the **generator**, which generates electrical power. The electricity produced by the main generator is transmitted to an adjacent **switchyard**, where a small portion is diverted back into the plant to drive pumps, conveyors, lighting, and such. The remainder begins a long journey that will eventually culminate in your home.

The Future of the Coal-Fired Power Plant

- ▶ The coal-fired power plant is a beautifully engineered infrastructure system that has served us well for more than a century. But this system faces an uncertain future, because of its adverse effects on our environment.
- ▶ Even though the past few decades have seen the development of highly effective clean-coal technologies, the challenge of carbon emission remains. However, a series of new technologies hold great promise for preserving the viability of power generation from fossil fuels. Even so, power companies are shutting down many older, less-efficient coal-fired plants in anticipation of stricter federal emission standards.

- ▶ Nonetheless, the impracticality of replacing all of our coal-based generating capacity in the short term and the real possibility of a technological solution to the carbon emission challenge suggest that coal will be part of our energy portfolio for many years to come.

TERMS

boil: To change from the liquid phase to the vapor phase.

chemical energy: A form of energy associated with the bonds between the atoms that constitute molecules.

condenser: A device that changes vapor into liquid by transferring heat from the fluid.

downcomer: A vertical pipe that circulates hot water from the steam drum back to the boiler in a steam power plant.

efficiency: In thermodynamics, a dimensionless measure of the effectiveness of an energy-conversion process in a device that uses thermal energy—e.g., an engine, a boiler, a furnace, or a refrigerator. In general, thermodynamic efficiency is calculated as a ratio of output to input and thus is always a number between 0 and 1 (or between 0% and 100%). Also called **thermal efficiency**.

elastic energy: A form of energy associated with the deformation of a material. Also called **strain energy**.

electrical energy: A form of potential energy associated with a difference in voltage.

electromagnetic radiation: A type of radiant energy emitted by current flowing through a conductor and other electromagnetic processes.

generator: A device that converts the kinetic energy of a rotating shaft into electrical energy.

heat exchanger: A device for transferring heat from one fluid to another, usually without allowing them to mix.

internal energy: A form of energy associated with the microscopic motions of the particles that constitute matter.

kinetic energy: The energy associated with a mass in motion.

nuclear energy: A form of energy associated with the bonds between the particles that constitute the atomic nucleus.

nuclear fission: A process in which an atomic nucleus splits into lighter nuclei and releases energy. In a fissile material, fission can occur spontaneously, or it can occur when the nucleus absorbs a free neutron.

potential energy: The energy associated with the elevation of a mass.

radiant energy: A form of energy associated with light and other forms of electromagnetic radiation.

reheater: In a steam power plant, a device that transfers heat from the furnace exhaust gases to the steam en route from the high-pressure turbine to the intermediate-pressure turbine.

riser: A vertically oriented water-filled steel tube integrated within the walls of the furnace in a steam power plant. A series of closely spaced risers form the walls of the boiler.

rotor: (1) In a steam turbine, a set of angled blades that rotates with the turbine shaft. The rotor interacts with a stator to produce shaft power. One stator and one rotor constitute one stage of the turbine. (2) In a generator, a rotating element on which one or more magnets are mounted. The rotor produces a varying magnetic field that induces an electrical current in the stator. (3) In a wind turbine, the assembly of rotating blades that drives the generator shaft.

stator: (1) In a steam turbine, a set of angled blades that are fixed to the turbine casing. The stator interacts with a rotor to produce shaft power. One stator and one rotor constitute one stage of the turbine. (2) In a generator, the stationary coil in which an electrical current is induced by the rotor.

steam drum: A device that separates high-pressure steam from boiling water in a steam power plant.

steam turbine: A mechanical device that converts the internal energy in steam into the kinetic energy of a rotating shaft.

superheater: In a steam power plant, a device that transfers heat from the furnace exhaust gases to the steam en route from the steam drum to the turbines.

switchyard: A facility that connects a power plant to its associated power transmission system. The principal function of the switchyard is to increase voltage for long-distance transmission.

turbine: An engine that produces continuous power by means of a fast-moving flow of water, steam, gas, or air driving a rotor fitted with vanes or blades.

voltage: A difference in electrical potential between two points, measured in volts. Voltage causes current to flow through a circuit.

work: Energy transferred through the movement of a force through a distance.

READINGS

Blume, *Electric Power System Basics*, chapters 1 and 2.

Hayes, *Infrastructure*, chapter 5.

Moran, Shapiro, Boettner, and Bailey, *Fundamentals of Engineering Thermodynamics*, chapters 1–5 and 8.

QUESTIONS

- 1 Given the environmental challenges associated with burning coal, why is coal still our principal fuel for electric power generation?
- 2 What are the two forms of interaction between electricity and magnetism that make power generation possible?

Oil, Gas, and Nuclear Power

The decline in coal-fired power production has been facilitated by dramatic developments in the energy industry. Trends in energy production are often both unpredictable and volatile, with drastic changes triggered by international conflicts, domestic political decisions, technological developments, technological failures, and changing societal values. Given this unpredictability, the diversity of our energy portfolio is one of its greatest strengths. And that's why, in this lecture, you will examine the three conventional power-generation alternatives to coal: oil, natural gas, and nuclear fission.

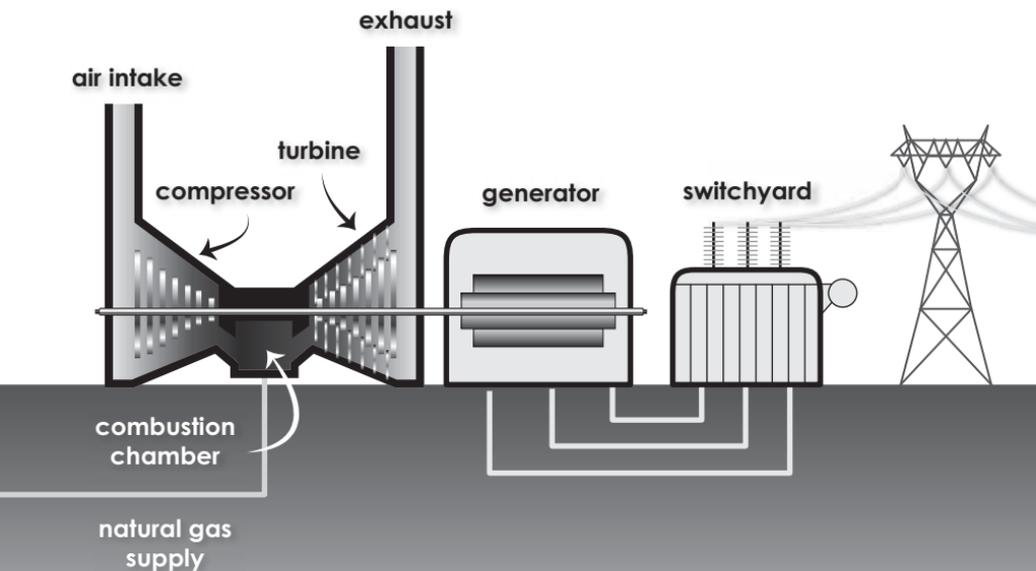
Power Generation from Oil

- ▶ Power generation from oil accounts for less than 1% of U.S. electrical power. The associated technology is similar to coal-fueled plants. Indeed, the only significant difference is that the coal furnace is replaced by an oil furnace, fueled by oil sprayed into the combustion chamber through a series of nozzles. The nozzles break up the stream of oil into tiny droplets for more complete combustion—just as pulverized coal is used to achieve better combustion in coal furnaces.
- ▶ Beyond the furnace, the operation of an oil-fired plant is essentially identical to that of a coal-fired plant. Heat from the furnace boils water, which is used to drive steam turbines, which drive generators to produce power. And burning oil carries with it the same major disadvantages—air pollution and carbon emissions—the inevitable by-products of the chemistry of combustion.
- ▶ An interesting benefit of oil-fired power generation is its use of a fuel that serves no other practical purpose: the thick, corrosive waste product of the petroleum refining process. This petrochemical sludge is a far cry from the light fuel oils used for home heating. It's so thick that it must be heated to more than 100°F just to move it through a pipeline. As such,

even though oil is likely to continue making only a minor contribution to U.S. power production, it will remain a useful means of disposing of an otherwise-useless waste product.

Power Generation from Natural Gas

- ▶ Natural gas currently fuels about 28% of U.S. power generation. The operation of a gas-fired power plant is fundamentally different from that of a coal- or oil-fired plant, in that it does not use the combustion of fossil fuel to boil water. Rather, it uses a fundamentally different type of turbine—called a **combustion turbine**—that's driven directly by the combustion of natural gas.
- ▶ In a typical gas-fired power plant, the turbine is composed of four major components: a compressor, a combustion system, a turbine, and a **driveshaft**. The compressor, rotated at high velocity by the spinning shaft, draws air through an intake, compresses it, and feeds it into a ring of combustion chambers. Fuel injectors introduce a steady stream of natural gas into the chambers, and the resulting mixture of gas and



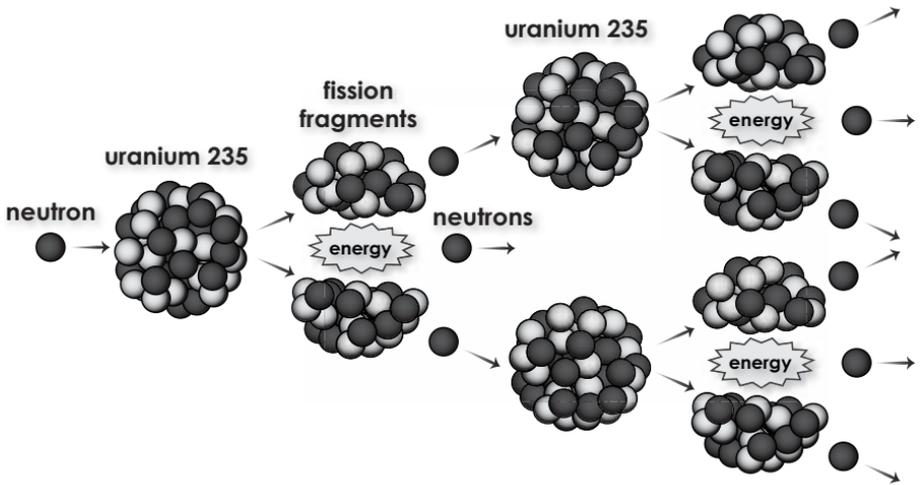
compressed air is burned at a temperature of more than 2000°F and then fed into the turbine.

- ▶ The hot, high-pressure exhaust gas expands through the turbine in essentially the same way that steam expands through a steam turbine—spinning the rotors, which drive the shaft, which powers both the compressor and the generator. The generator sends **three-phase power** to the adjacent switchyard, just like a coal-fired plant.
- ▶ The **thermodynamic efficiency** of a combustion turbine is somewhat less than that of a steam turbine; however, the efficiency of the power-generation system can be improved significantly by adding a piece of equipment—called a heat recovery **steam generator**—which captures waste heat from the turbine exhaust and uses it to produce steam that drives a conventional steam turbine. This configuration is called a combined-cycle power plant.
- ▶ Natural gas has three significant advantages over coal as a fuel for power generation.
 - The combustion of gas is significantly cleaner than the combustion of coal.
 - A natural gas-fired plant has a much smaller physical footprint than a coal-fired plant with the same power output. For this reason, gas-fired plants have been particularly popular in urban areas with limited space.
 - A combustion turbine can be started up and shut down easily and quickly, while starting up a coal furnace takes the better part of a day. As a result, coal-fired plants are designed to run 24 hours per day and to shut down only for maintenance.
- ▶ Even though gas is much cleaner than coal, burning natural gas still emits pollutants and relatively large amounts of carbon dioxide. In this sense, nuclear, hydroelectric, wind, solar, and **geothermal power generation** are all superior, because they produce no emissions at all. Combustion turbines are also extremely loud. And, most importantly,

there are serious environmental concerns about fracking, the technology underlying the ongoing natural gas production boom.

Nuclear Power

- ▶ Nuclear power is the source of roughly 20% of the electrical power that is used in the United States and 13% worldwide. With 99 reactors at 61 nuclear power plants nationwide, the United States is currently the world's largest supplier of commercial nuclear power, in terms of raw output.
- ▶ A nuclear power plant is similar to a coal-fired plant, in the sense that both use closed-loop steam cycles to spin turbines. The big difference is the source of energy used to produce the steam: chemical energy for a coal-fired plant and nuclear fission for a nuclear plant.
- ▶ Nuclear fission—the splitting of atomic nuclei—depends on the unique behavior of certain heavy elements, called **fissile materials**, which are used as nuclear fuel. A fissile material is one that's capable of sustaining the chain reaction associated with nuclear fission.
- ▶ The most common fissile material is **uranium 235**. When the nucleus of a uranium 235 atom is struck by a neutron, it breaks apart, releases energy, and emits a few free neutrons. If a sufficient quantity of this material is assembled in one place, the neutrons emitted by the fission of one nucleus will encounter adjacent nuclei, causing them to split, release energy, and emit more neutrons. As this process continues, progressively more free neutrons cause the fission of progressively more nuclei. The result is a **nuclear chain reaction**—self-sustaining fission.
- ▶ If this chain reaction is controlled, we have a very potent source of energy; if it's uncontrolled, we have a nuclear explosion. But how does this reaction get started? Uranium 235 experiences a small amount of spontaneous fission, a natural form of radioactive decay that releases a few neutrons. We only need to assemble a critical mass of uranium 235, and this natural emission of neutrons will set the nuclear chain reaction in motion.



- ▶ Nuclear fuel is prepared for use in a reactor by molding uranium into small pellets, which are then sealed inside metal tubes to create **fuel rods**. The tubes are made of zirconium alloy, which is used because of its corrosion resistance and low neutron absorption. The purpose of the tube is to contain the uranium pellets so that fragments can't break away and contaminate the reactor coolant.
- ▶ The fuel rods are assembled into bundles of about 200 each, and about 150 such bundles are combined to form the **reactor core**. The holes in each bundle allow for the insertion of **control rods**, which are cylindrical bars made of boron carbide, a material that's particularly effective at absorbing neutrons. When the control rods are inserted into a fuel bundle, they absorb enough free neutrons to prevent the fission reaction from sustaining itself. Thus, they keep the nuclear reaction from getting out of control. When they're withdrawn, they allow the reaction to proceed.
- ▶ From a macro perspective, the advantages of nuclear power are considerable. Nuclear plants can operate at maximum capacity for extended periods of time, so they're very effective at meeting the

base load. Although nuclear fuel is a nonrenewable resource, there's enough of it in the Earth's crust to last for centuries. More importantly, properly contained nuclear fission produces minimal air pollution and no carbon dioxide.

- ▶ In the first decade of the 21st century, a growing appreciation for these advantages—coupled with post-9/11 concerns about our dependence on energy sources from unstable regions of the world—led to a resurgence in enthusiasm for nuclear power, both in the United States and abroad. Many new power-plant construction projects were initiated. There was talk of nuclear power as a major component of a new environmentally friendly power-generation system.

nuclear power plant



- ▶ And then came the 2011 Fukushima power plant disaster, throwing the nuclear industry back on its heels once again. Tragically, 50 minutes after a magnitude-9.0 earthquake off the coast of Japan, an earthquake-induced tsunami overtopped the plant's protective seawall and flooded the facility, causing the emergency generators to fail. The plant's backup battery system immediately took over, but when the batteries went dead the following day, there was nothing to prevent all three reactor cores from melting down. The result was a humanitarian, environmental, and economic catastrophe.
- ▶ Beyond the potential for nuclear accidents, the long-term viability of nuclear power is also plagued by the still-unresolved challenge of nuclear waste disposal. This challenge is exacerbated by the high level of radioactivity in the products of nuclear fission.
- ▶ These serious challenges notwithstanding, nuclear power is not going away anytime soon. Even in places where nuclear power has fallen out of favor, the immense capital investment in existing plants provides a strong incentive to keep them in operation for as long as possible.

TERMS

combustion turbine: A turbine engine that is propelled directly by the combustion of natural gas.

control rod: In nuclear power generation, a boron carbide rod that slows or stops the nuclear chain reaction by absorbing neutrons when inserted into the reactor core.

driveshaft: In an automobile drivetrain, a shaft that connects the transmission to the differential.

fissile material: A material (e.g., uranium 235) that is capable of sustaining the chain reaction associated with nuclear fission.

geothermal power generation: The generation of electrical power from naturally occurring heat below the Earth's surface.

nuclear chain reaction: A self-sustaining process that occurs when neutrons emitted by the fission of atomic nuclei encounter adjacent nuclei and cause them to split and emit more neutrons.

reactor core: In nuclear power generation, the vessel in which the nuclear reaction takes place. The reactor core contains nuclear fuel rods and control rods.

steam generator: A device that transfers heat from the primary loop to the secondary loop in a pressurized water reactor.

thermodynamic efficiency: A dimensionless measure of the effectiveness of an energy-conversion process in a device that uses thermal energy—e.g., an engine, a boiler, a furnace, or a refrigerator. In general, thermodynamic efficiency is calculated as a ratio of output to input and thus is always a number between 0 and 1 (or between 0% and 100%). Also called **thermal efficiency**.

three-phase power: Electric power generated, transmitted, and distributed through three conductors, each carrying an alternating current (AC) of the same frequency and voltage, but each out of phase with the other two by 120°.

uranium 235: The most commonly used fissile material for nuclear power generation.

READINGS

Blume, *Electric Power System Basics*, chapter 2.

Hayes, *Infrastructure*, chapter 5.

Moran, Shapiro, Boettner, and Bailey, *Fundamentals of Engineering Thermodynamics*, chapters 1–5, 8, and 9.

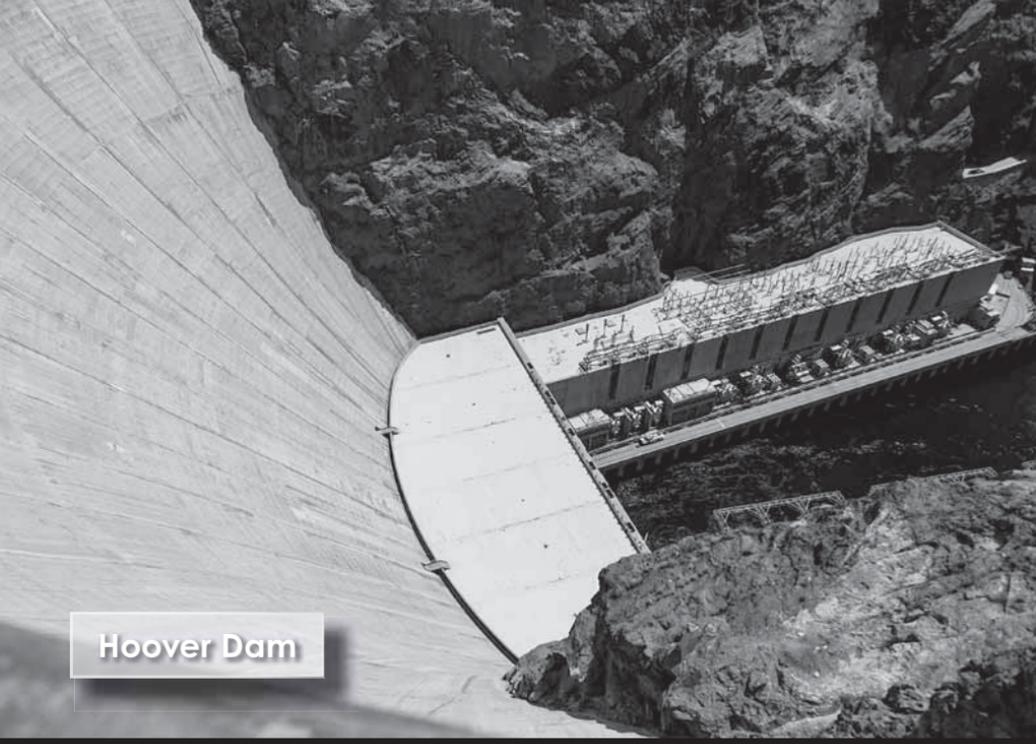
QUESTIONS

- 1 How do the relative strengths and weaknesses of coal, natural gas, and nuclear power generation complement each other?
- 2 What are some positive aspects of our growing reliance on natural gas for electric power generation? What are the dangers?

In this lecture, you will learn about the three most important sources of renewable energy: hydropower, wind power, and solar power. The term “renewable energy” refers to energy produced from resources that are naturally replenished on a human timescale. Consistent with this definition, hydropower is renewable, because water flowing through a hydroelectric-generating facility is rapidly replenished by rain falling on the associated watershed. Wind power is renewable because naturally occurring differences in atmospheric pressure produce an inexhaustible supply of moving air. Solar power is renewable, because the Sun continuously bombards the Earth with more energy than we can possibly use.

Hydroelectric Power

- ▶ Hydroelectric power is our oldest form of **renewable energy** and also our most prevalent, representing about 7% of all electric power generated in the United States.
- ▶ Waterpower has been used since at least the 3rd century B.C., and through the 19th century, it was used extensively for such applications as milling grain, sawing lumber, and powering textile machinery. Extensive as they were, these uses of hydropower were all fundamentally limited by a common constraint: Power had to be consumed at the same location where it was generated.
- ▶ This constraint was eliminated with the development of hydroelectric power in the late 19th century, and from the early 20th century onward, hydropower has been used almost exclusively to generate electricity. By the 1930s, hydroelectricity accounted for 40% of the power used in the United States. And while our hydropower capacity has increased in absolute terms since then, the proportion of power generated from this source has fallen dramatically, from 40% to 7%.



Hoover Dam

- ▶ U.S. hydropower generation has remained essentially constant since the early 1970s, in part because many of the best sites have already been exploited, but also because of fierce environmental opposition to the construction of dams. Still, given the immense capital investment in these facilities, hydroelectricity will remain an important contributor to worldwide power generation for the foreseeable future.
- ▶ A modern hydroelectric power plant requires a dam, capable of impounding a large quantity of water at a height significantly above the normal level of the watercourse. The higher the water level, the greater the potential energy available for conversion into electricity.
- ▶ A carefully controlled quantity of water is drawn from one or more intake structures behind the dam and then is routed into large steel tubes called **penstocks**, each of which carries a stream of water at high velocity down to a water turbine, which turns a generator to produce electricity.

- ▶ Hydroelectricity has many significant advantages over other forms of power generation. It's safe and produces no emissions. Water turbines can be started up and shut down very rapidly; thus, hydropower can be very responsive to fluctuations in demand. And the reservoirs created for hydropower generation often provide additional economic benefits, such as irrigation, water supply, flood control, navigation, and recreation.
- ▶ However, the adverse environmental impacts of dams remain problematic. Dams inundate large areas of land, which may include important human cultural artifacts and wildlife habitats; interrupt fish migration patterns; and can kill juvenile fish that get sucked into the turbines.
- ▶ This adverse impact on fish has been well understood since the late 19th century, and a wide range of technological solutions have been tried, at considerable cost, but with only mixed success. The combined impact of environmental damage and the limited availability of new hydropower-compatible sites suggests that this particular form of renewable energy has little potential for long-term growth.

Wind Power

- ▶ Like hydropower, wind power also has a long history, but the technology has seen dramatic leaps forward in just the past decade. The modern **wind turbine** seems the epitome of simplicity. A large three-bladed rotor is mounted atop a tall steel pylon. The rotor is spun by moving air, and the rotor shaft turns a generator located within a housing called a **nacelle**.
- ▶ Yet behind this apparent simplicity is some highly sophisticated engineering. Each blade of a modern wind turbine is designed like an airplane wing, with an airfoil that's capable of generating lift as air flows across it. This lifting force pulls the blade through its circular path, spinning the rotor. This is efficient because lift increases with increasing blade velocity.
- ▶ To maximize their aerodynamic efficiency, wind turbine blades must be long, thin, and light—yet strong enough to resist very high mechanical

stresses. Thus, they must be fabricated of specialized materials, typically high-strength epoxy-based fiberglass, very similar to the wings of high-performance gliders or sailplanes. To maximize aerodynamic efficiency, the rotor also must be oriented into the wind at all times.

- ▶ The generator must meet two challenges unique to wind turbine design. First, most large wind turbines only rotate at about 20 revolutions per minute—much too slow for commercial power generation, which requires 60 revolutions per second. Thus, the **drivetrain** must incorporate a gearbox that increases the generator's speed of rotation.
- ▶ Second, for commercial power generation, the shaft's speed of rotation must be constant—quite a challenge, because the wind speed is constantly changing. To control the rotor speed, a sensor on the nacelle continuously monitors the wind velocity, and computer-controlled motors adjust the pitch angle of the rotor blades to keep the velocity constant.
- ▶ As an engineered system and as a generator of renewable energy, a wind turbine is a beautiful thing. It converts the kinetic energy of moving air directly into electrical power with no combustion and no emissions. It's no wonder that wind power production has tripled in the past 5 years and now constitutes about 4% of the world's total power output.

wind turbines

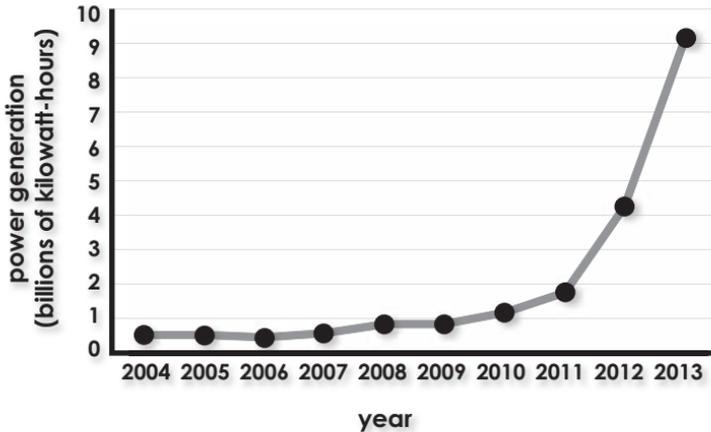


- ▶ Still, wind power is not without limitations. A typical commercial wind turbine used in the United States today has a generating capacity of 1.5 megawatts. A large coal-fired power plant generates 1500 megawatts. Thus, to provide the same generating capacity as that single coal-fired plant, we need at least 1000 of these typical wind turbines.
- ▶ That's why commercially viable power generation requires wind farms, consisting of tens or hundreds of turbines. These installations have drawn considerable opposition, because of their visual impact, noise, and hazard to birds. Wind farms also consume large tracts of land area.
- ▶ Such concerns are being addressed, in part, by the development of larger, more powerful turbines and by increased use of offshore wind farms, which reduce both noise and visual impact while taking advantage of stronger and steadier winds. But offshore wind farms come with their own challenges, including significantly higher construction costs, potentially greater visual impact, and interference with fishing, recreation, and offshore oil and gas drilling.
- ▶ More importantly, because wind is geographically variable, only certain locations are economically suitable for wind power generation. And because wind is variable over time, it can't produce a predictable, steady level of power at any location. Because of these limitations, it's unlikely that wind will account for more than 10% of U.S. power generation over the next few decades.

Solar Power

- ▶ The form of renewable energy with the greatest potential for future expansion is **solar power**. The Sun provides the Earth's surface with a steady stream of more than 800 billion megawatts of energy, nearly 100,000 times more than current total worldwide power production.

U.S. Solar Power Generation



- ▶ There are two general categories of solar power: **solar-thermal power** and **photovoltaics**. In general, solar-thermal power is produced by using mirrors to concentrate the Sun's rays onto a single point, producing enough heat to generate electrical power.
- ▶ Unlike solar-thermal power, which uses the Sun's energy to boil water, drive turbines, and turn generators, photovoltaics generates electricity directly from solar radiation with no moving parts.
- ▶ The **photovoltaic effect** occurs in certain types of semiconductor materials, such as silicon. Photons impinging on this material excite electrons to higher states of energy, effectively knocking them loose from their atoms. In a photovoltaic device, these free electrons are captured in an adjoining material, where they constitute an electric **current**. By its nature, the photovoltaic effect produces **direct current**, just like a battery.



solar panels

- ▶ Photovoltaic material is packaged in solar cells, and when more power is required than a single cell can deliver, multiple solar cells are assembled into photovoltaic modules, commonly known as **solar panels**.
- ▶ Most of the recent growth in photovoltaics has been in small-scale solar panel installations like the ones that have become so common on residential and commercial buildings. Rooftop solar arrays are inherently less efficient than large-scale solar farms, because they can't be rotated to follow the Sun. Nonetheless, from an economic perspective, consumer-installed photovoltaics have a huge advantage. Many homeowners can recover the up-front cost of installing a solar array through savings in energy cost within just a few years.
- ▶ Its obvious advantages notwithstanding, solar power also has its own unique limitations. Most importantly, all forms of solar power rely on a source of energy that's only available when the Sun shines. For the foreseeable future, large-scale solar power generation will probably be

economically feasible only in regions that experience intense sunlight for a large proportion of the year. While we should expect to see continued robust growth in solar power generation, full exploitation on a national scale won't happen without significant improvements in our ability to move power efficiently over long distances.

TERMS

current: The flow of electrons through a conductor when subjected to a voltage. Current is measured in amperes, or amps.

direct current (DC): A steady, unvarying current, as is produced by a battery.

drivetrain: An integrated series of automotive components that transmit mechanical power from the engine to the drive wheels. The drivetrain consists of the flywheel, clutch, transmission, driveshaft, differential, and drive axles.

nacelle: A streamlined housing that encloses the generator of a wind turbine.

penstock: In hydroelectric power generation, a large tube that transmits water at high velocity from the reservoir to a turbine.

photovoltaic effect: An effect that occurs when photons impinging on a semiconductor (e.g., silicon) excite electrons to higher states of energy. In a photovoltaic device, these free electrons are captured in an adjoining material, where they constitute an electric current.

photovoltaics: Technologies that use solar cells to convert solar radiation directly into electricity through the photovoltaic effect.

renewable energy: Energy produced from resources that are naturally replenished on a human timescale.

solar panel: A device for generating electricity through the photovoltaic effect. A solar panel consists of an array of solar cells.

solar power: The conversion of solar radiation into electrical energy. The two principal forms of solar power are solar-thermal power and photovoltaics.

solar-thermal power: A form of solar power generation in which mirrors are used to concentrate the Sun's rays onto a single point, producing enough heat to generate electricity.

wind turbine: A device that converts the kinetic energy in moving air into electrical power.

READINGS

Blume, *Electric Power System Basics*, chapter 2.

Hayes, *Infrastructure*, chapter 5.

QUESTIONS

- 1 What are the relative advantages and disadvantages of the solar-thermal versus photovoltaic forms of solar power generation?
- 2 How does wind power illustrate the inherent ambiguity in the concept of “environmental friendliness”?

Electrical Power Transmission: The Grid

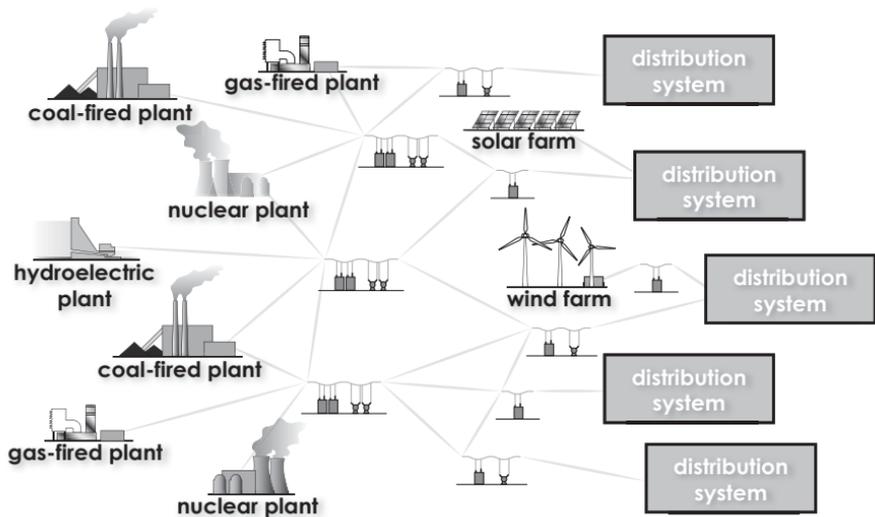
One reason why electricity has become the common currency of our energy-intensive world is that electrical power is uniquely transportable: It can be readily moved across long distances from its point of generation to its point of use, via an infrastructure system called the grid, which is a vast network of power plants, substations, and transmission lines serving a large geographic area. In this lecture, you will be introduced to this system, with a focus on power transmission, from the power plant to your local substation.

The Grid

- ▶ Power produced by a generating plant is first transmitted to the adjacent switchyard, where **transformers** are used to boost the voltage to a very high level—typically in the range of 115,000 to 765,000 volts. High-voltage power is then moved over long distances by **conductors**, called transmission **feeders**, which are suspended from steel towers.
- ▶ Transmission feeders terminate at regional **substations**, located near the cities, towns, or industrial facilities where the power will be consumed. At each substation, transformers are used to step the voltage down to an intermediate level—typically between 35,000 and 138,000 volts—for sub-transmission to a series of smaller substations located closer to consumers.
- ▶ At these local substations, the voltage is lowered yet again—typically to 2400 to 25,000 volts—for distribution to individual commercial and residential users, normally by overhead lines supported on wooden poles.
- ▶ Finally, just outside your home, the power is stepped down once more—to 120 volts (or 230 volts if you live in Europe)—and fed into your residential electrical system.

the grid



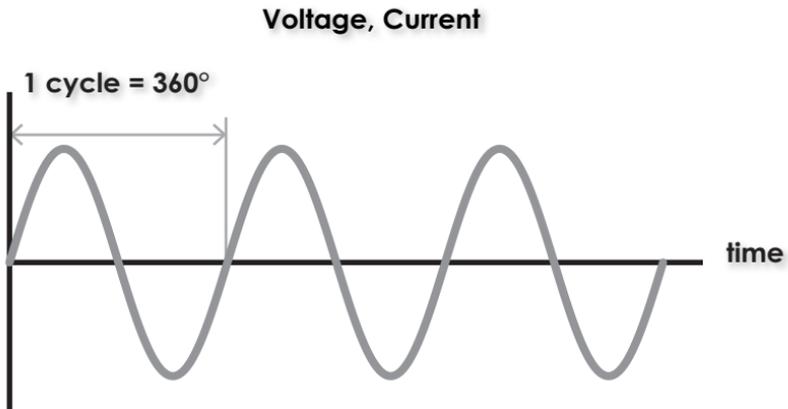


- ▶ This overview might suggest that power transmission is a simple, linear process, but in practice, it's anything but. The **grid** is, by definition, a meshed network, with many generating facilities supplying power to many interconnected substations, for enhanced redundancy and flexibility.
- ▶ The geographic extent of a regional grid is vast. The United States and Canada are served by just five such networks, called **interconnections**. The size and networked structure of these interconnections offer three powerful advantages.
 - The regional grid can accommodate the widely varying operating characteristics of all types of power-generation systems—fossil fuel, nuclear, and renewable.
 - If a generating source or transmission feeder is shut down or damaged, power is automatically rerouted, finding alternative paths to maintain service at the local substations.

- The network can move power across long distances to accommodate local variations in both production and demand or to facilitate the purchase of bulk power at reduced cost from distant producers that are able to generate more efficiently.

Three-Phase Power

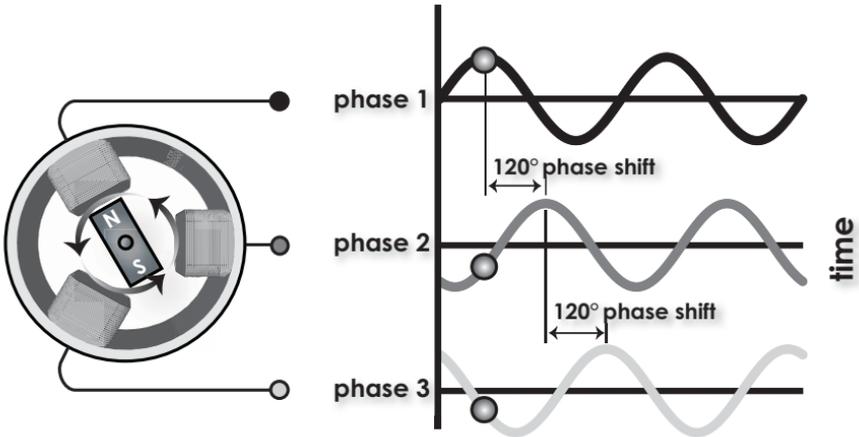
- ▶ A battery produces direct current (DC), an unvarying one-way flow of electrons through the **circuit**. Conversely, a generator produces **alternating current** (AC), by rotating a magnet adjacent to a coil of wire mounted on a stationary housing called the stator. The continuously varying magnetic field produces continuously varying current and voltage, which can be represented mathematically by a sine curve, as shown here.



- ▶ The sine curve illustrates three critically important physical characteristics of AC power.
 - The variation in voltage and current repeats itself, with one cycle for each full 360° rotation of the generator shaft.

- If the shaft is turning at constant speed, the voltage and current undergo a constant number of cycles within a specified **period** of time. This is called the **frequency**, and within an electrical power system, the frequency is always standardized.
 - The current changes direction twice per cycle. It first flows away from the generator, then toward it, and then away again. This is counterintuitive. We tend to think of electrical power flowing in one direction from the generator through transmission lines to our homes. But in an AC power system, the electrons aren't flowing anywhere; they're just sloshing back and forth in the conductor.
- This phenomenon is essential for our understanding of three-phase power, a defining feature of modern AC power systems. Typically, three-phase power is produced by a generator with a specific configuration. Three coils are equally spaced around the stator, with each coil connected to a separate conductor. An **electromagnet**, with one pair of north and south magnetic poles, is mounted on the rotor.

three-phase generator



- ▶ To achieve the U.S.-standard frequency of 60 hertz, the turbine-driven rotor must spin at exactly 60 revolutions per second, and the rotating magnetic field produces a sinusoidally varying voltage in each coil.
- ▶ This is three-phase AC power: the simultaneous generation of three sinusoidal voltages (called phases) on three parallel conductors. All three phases have the same maximum voltage and the same frequency, with each cycle corresponding to one full 360° rotation of the generator shaft. But each sine curve is shifted by one-third of a cycle. This is called a 120° phase shift, because each curve is shifted by one-third of the 360° cycle.
- ▶ Three-phase AC power is by far the most common form of power transmission throughout the world. It is ubiquitous because it's so much more efficient than single-phase power, which always requires two conductors, one that supplies power to the load and one that provides a return path to complete the circuit.
- ▶ Three-phase power doesn't require a separate conductor to complete the circuit, because of an amazing mathematical property of the sine curve: When three sine curves have a 120° phase shift with respect to each other, the three curves add to zero at every point in time.
- ▶ Thanks to this property, three-phase power doesn't require any additional conductors to complete the circuit, because the three phase conductors provide return paths for each other. Current flowing toward the load in one phase is always counterbalanced by current flowing away from the load in one or both of the other two phases.
- ▶ Thus, in comparison with a single-phase transmission system requiring two conductors, a three-phase system delivers three times the power with only one additional conductor—a substantial improvement in cost efficiency.
- ▶ Three-phase power results directly from the physical configuration of the power-plant generator, with its three coils on the stator and single magnet on the rotor. But this system produces power at the standard 60-hertz frequency only if the generator shaft can spin at exactly 60

revolutions per second. Steam turbines and combustion turbines achieve this speed easily, but water turbines and wind turbines can't. Wind turbines typically address this problem by adding a gearbox between the turbine and the generator. But in a hydroelectric generator, additional magnetic poles are added to the rotor.

- ▶ With the concept of three-phase power as background, we can now appreciate the two most astonishing characteristics of a modern electrical power grid.
 - Within each of these vast geographical interconnections, all of the grid-connected generators must spin in perfect synchronization—all at 60 revolutions per second and all in phase, as well. Basically, the sine curves produced by these hundreds of generators at widely dispersed locations must all line up perfectly, as if the generators were all turning on the same shaft.
 - The total electrical power generated within a regional grid must exactly meet the total demand for power at any given time. Thus, when you pop a slice of bread into your toaster, the slightly increased demand for power slows down the generator at a faraway power plant, just a tad. In response, an automatic control system increases the flow of steam into the adjoining turbine, adding just enough **torque** to the generator shaft to restore the correct 60-hertz frequency. This delicate balancing act is happening nonstop across the entire grid.
- ▶ The grid isn't perfect, as evidenced by the occasional regional blackouts that occur when these control systems go awry. But, in a sense, the rarity of such events underscores how well the system serves us on a day-to-day basis.
- ▶ Given the challenge in synchronizing AC power throughout a regional grid, why do we use AC power in the first place? Why not just use DC, which would require no synchronization at all? One important reason is that an essential transmission technology—the transformer—only works with AC power, and without transformers, we wouldn't be able to boost the voltage sufficiently to prevent unacceptable power losses during transmission.

- ▶ DC is used for two specialized purposes in our power system. The first is to create connecting links between the regional AC grids so that power can be moved between regional grids without having to synchronize its frequency and phase. The second is to use high-voltage DC for transmitting power across very long distances, because DC is somewhat more efficient than AC for this purpose.

Conductors and Transmission Towers

- ▶ In addition to transformers, the other major components of the transmission grid are conductors and transmission towers. In an earlier era, high-voltage conductors were made of copper because of its low electrical resistance. Today, they're typically twisted strands of heavy aluminum wire with a steel core for added tensile strength. Aluminum has higher electrical resistance than copper, but it's a lot lighter, which significantly reduces the structural loads on the transmission towers.
- ▶ For extremely high-voltage feeders, each phase is composed of a bundle of two or more individual conductors. At high voltages, using several smaller conductors in lieu of one larger one reduces power loss and enhances cooling.
- ▶ High-voltage conductors don't have an insulated outer sheath; they are insulated by the surrounding air, which is why they need to be suspended far above the ground. And that's the job of the transmission tower, the utilitarian steel structure that has become such an integral part of our modern landscape.
- ▶ The structural design of the tower must account for the considerable weight of the transmission lines, as well as the effects of wind and wind-induced vibration, ice accumulation, and earthquakes. Given the significant regional variations in these environmental loadings, it's hardly surprising that transmission towers exhibit a wide variety of structural configurations.



transmission tower

TERMS

alternating current (AC): A current that varies continuously in a recurring sinusoidal cycle, typically because it is produced by a rotating generator.

circuit: (1) An electrical conductor formed into a closed loop, thus allowing current to flow in response to a voltage. (2) A telecommunications channel that is transmitted on a physical medium (e.g., copper wire, coaxial cable, or optical fiber).

conductor: A metal wire or cable that provides a path for the flow of electric current.

electromagnet: A magnet that uses the magnetic field produced by an electrical current flowing through a conductor.

feeder: A main electrical power supply line in either a power transmission or distribution system.

frequency: For any cyclic phenomenon, the number of alternating cycles occurring within a given period of time. Frequency is expressed in hertz or cycles per second and is the reciprocal of the period.

grid: A network of power plants, substations, and transmission lines serving a large geographic area.

interconnection: A major regional electric power grid that operates at a synchronized frequency.

period: For any cyclic phenomenon, the time required for one full cycle. The period is the reciprocal of the frequency.

substation: A facility that serves as a node in an electrical power transmission or distribution network. Substations may incorporate switches (or circuit breakers), transformers, and a variety of other devices for power management.

torque: A moment applied to a shaft, measured in units of force times distance.

transformer: A device that either raises or lowers electric voltage.

READINGS

Blume, *Electric Power System Basics*, chapters 3, 4, 5, and 7.

Hayes, *Infrastructure*, chapter 5.

QUESTIONS

- 1** Find a high-voltage power transmission line in your neighborhood or region. How many three-phase feeders does it include? What is the configuration of the towers? Is each phase a single conductor or a bundle of two or more conductors? What is the configuration of the insulators?
- 2** Using Google Earth software or other online satellite imagery, locate a power transmission line in your neighborhood or region and trace it back to the nearest power plant. From the satellite image, can you identify what type of power plant it is?

Electrical Power Distribution

In the previous lecture, you followed the transmission of high-voltage electrical power from the generating plant to a substation in your town. Now, the relentless flow of electrons continues as you examine electrical power distribution, a process that begins at the substation—which typically serves several hundred to as many as a few thousand homes and businesses—and ends at the electric meter mounted on an exterior wall of your home.

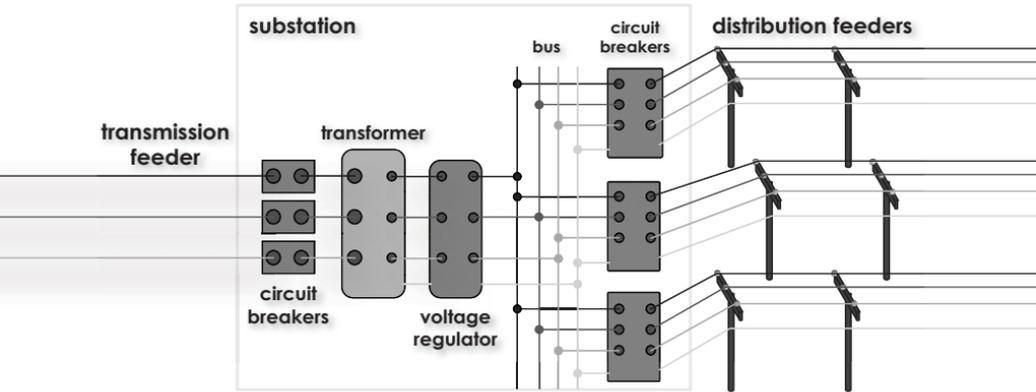
The Substation

- ▶ The substation's largest and most important piece of equipment is the transformer. Transformers are used at power-plant switchyards to step up voltage for transmission and then at substations to step it back down for distribution and consumption.
- ▶ A transformer consists of two coils of copper wire wrapped around an iron core, with the ratio of windings in the two coils determining the change in voltage. To change the voltage of three-phase power, each phase requires its own pair of coils. This can be accomplished either by placing all three pairs inside a single cabinet to create a three-phase transformer or by placing each pair in its own cabinet and then grouping three of these single-phase transformers together.
- ▶ In either case, electrical current flows into and out of the transformer through **bushings**, each composed of a solid copper conductor surrounded by glazed ceramic **insulators**. The purpose of the bushing is to prevent **flashover**—which occurs when a large voltage difference between two closely spaced conductors causes a white-hot electrical arc to jump the gap between the conductors—by providing an insulated conduit for current to pass through the transformer's grounded metal cabinet. Susceptibility to flashover increases with voltage and decreases with the size of the gap, so a higher-voltage conductor requires a larger bushing.



transformer

- ▶ High-voltage three-phase power from one or more transmission feeders enters the substation, passing through a set of **circuit breakers** before entering the transformer. The purpose of a circuit breaker is to interrupt the current in a conductor, either for routine maintenance or to prevent damage to transformers, generators, and other expensive equipment when abnormal events, such as **short circuits** and lightning strikes, occur in the conductor. Such events are called **faults**.
- ▶ To fulfill both of these functions, the circuit breaker must be capable of operating both manually and automatically. In the latter case, elaborate protective systems at the substation are constantly monitoring voltage and current; if either exceeds prescribed thresholds, the relays send signals to trip the appropriate circuit breaker, de-energizing the associated feeder until the fault can be fixed. These control systems are all battery powered, so they'll still work when the AC power system is out of service.



- ▶ Another component of the substation's protective system is the **lightning arrester**, which is typically placed where transmission feeders enter the facility and on the pathways into each major piece of equipment within. Lightning arresters are designed to protect substation equipment from voltage surges caused by lightning strikes occurring on the upstream transmission feeders. In effect, the arresters provide a second line of defense, backing up those **shield wires** mounted on the transmission towers.

- ▶ A **voltage regulator** is connected to the low-voltage side of the transformer. The regulator's purpose is to make minor adjustments in the distribution voltage in response to variations in load. The regulator is essentially a transformer that can vary the number of turns in its output coil, thus allowing for small adjustments to the output voltage in response to fluctuations in demand.

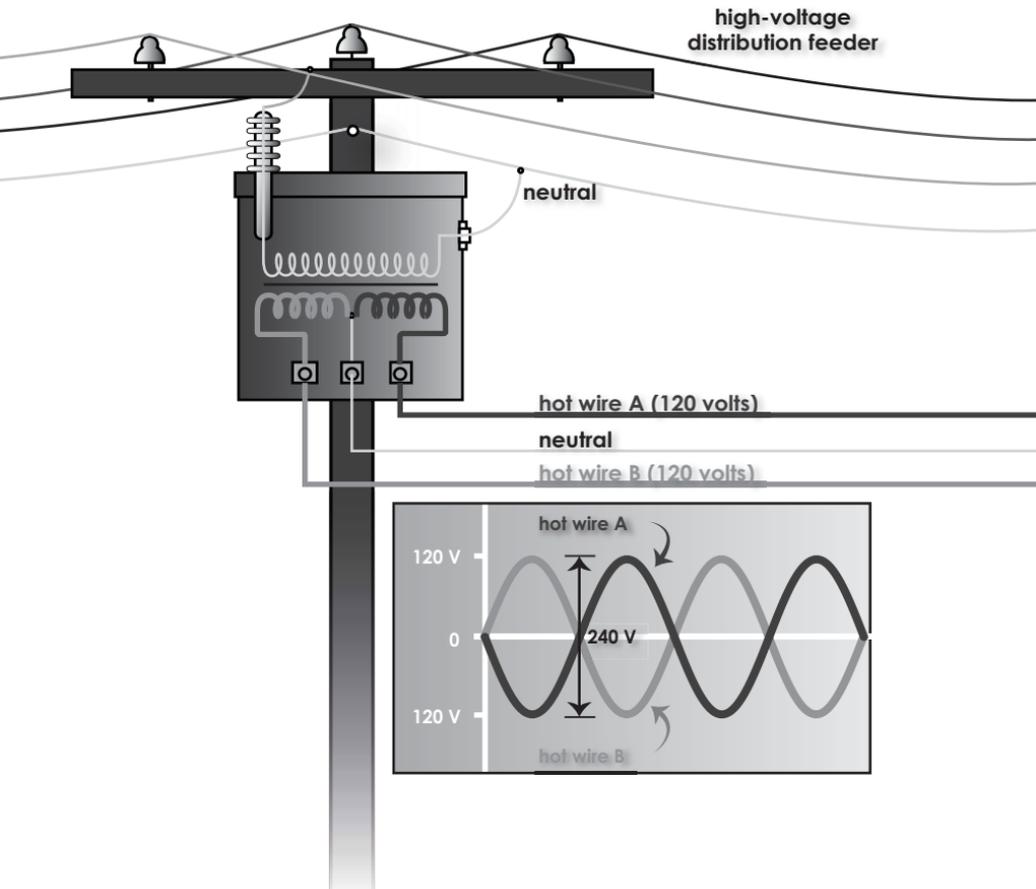
- ▶ Beyond the regulator, there's a grid of overhead conductors that distribute power to multiple distribution feeders, one of which serves your neighborhood. These conductors are called **buses**, and they're typically made of flexible aluminum cable or rigid aluminum tubing. In either case, one bus is composed of three parallel conductors—one for each phase—mounted on ceramic insulator posts, which are supported, in turn, by an extensive steel framework.

- ▶ It's common for a substation to incorporate at least two primary buses to provide redundancy. Incoming power can then be directed onto either bus. Transformers can draw power from either one, and as a result, power can always be rerouted around any device that has failed or been taken out of service.
- ▶ To facilitate rerouting power, the bus system incorporates many disconnect **switches** (also called isolators or cutouts), which are used to open and close connections between conductors in order to isolate individual pieces of equipment in the substation. The switches are typically simple hinged bars, which have no protection against flashover, so they can only be operated after the associated conductor has been de-energized by opening a circuit breaker.
- ▶ At the far end of the substation, we find another set of circuit breakers, one set for each distribution feeder. These breakers serve both to protect the system from faults and to manually de-energize a distribution feeder for maintenance or repair.
- ▶ Like transmission feeders, the distribution feeders are usually composed of bare aluminum cable, but this is where the similarity ends, in three important ways.
 - Distribution feeders are usually arranged radially, not in a meshed network like transmission feeders. Thus, if there's a problem on a particular distribution line, there's a good chance that all of the consumers served by that line are going to lose power.
 - Distribution feeders carry power at much lower voltages than transmission feeders; consequently, minimum conductor-spacing and ground-clearance requirements for distribution are considerably less demanding. That's why distribution feeders can be carried on simple wooden poles, rather than elaborate steel towers.
 - Unlike transmission feeders, which use three conductors each, distribution feeders use four—one for each phase, plus a **neutral** wire.

The Power Distribution System

- ▶ Every power distribution system consists of two principal subdivisions, called primary and secondary. The primary system consists of the distribution feeders and associated equipment for system protection and control. It extends from the substation to the immediate vicinity of your home, where a pole-mounted transformer steps the voltage down to its final level of 120 volts. From this point, the secondary distribution system brings power directly to your home.
- ▶ Integral to both primary and secondary distribution is a ubiquitous element of the modern American industrial landscape: the wooden utility pole. The principal purpose of utility poles is power distribution.
- ▶ At the top are the distribution feeders, which have the highest voltage of anything on the pole and therefore must be farthest from the ground. Immediately below is the single neutral wire. The distribution feeders are usually arranged in groups of three conductors and are mounted on ceramic insulators to maintain appropriate separation from the supporting crossbeams.
- ▶ We see insulators of many different sizes, shapes, and spacings on our local utility poles. In most cases, these variations reflect corresponding variations in distribution voltages.
- ▶ All of the technological components we encountered at the substation can also be found in the primary distribution system, albeit in smaller and simpler form. The pole-mounted transformer receives high-voltage input from one primary conductor above and sends its low-voltage output to the secondary distribution system below.
- ▶ Like its big brother at the substation, the pole-mounted transformer is susceptible to damage from lightning strikes, short circuits, and other abnormal conditions. Transformers are protected by lightning arresters and **fuses**. The lightning arrester works just like the larger ones at the substation. The fuse serves essentially the same protective function as a circuit breaker, except it can only be used once.

- ▶ A more technologically sophisticated protective device is a **recloser**, a type of circuit breaker that incorporates the system-protection equipment necessary to detect a fault, trip open in response, and then reclose automatically after a preprogrammed interval of time.
- ▶ In North America, the typical single-phase pole-mounted transformer receives its high-voltage input from one of the three feeder conductors and from the neutral wire. Its low-voltage output consists of two 120-volt “hot wires,” plus a neutral wire.



- ▶ Internally, the transformer produces this output by using two secondary coils connected together at the neutral wire. Because of this configuration, the voltage in the two hot wires is 180° out of phase, so there's a 240-volt difference between them. That's why the 120-volt power entering your home can be used to power 240-volt appliances as well as your standard 120-volt gadgets.

- ▶ The secondary distribution line that emerges from the pole-mounted transformer and carries power to your home is called a **service drop**. Each drop serves one building, and each enters the building through a fitting, called a **weatherhead**, which keeps precipitation out and provides a conduit down to the electric meter.



Your Electric Meter

- ▶ Power distribution terminates at your electric meter, which measures your power consumption for billing purposes. Beyond this point, the two hot wires and neutral wire are routed to your main service panel. The neutral wire is connected to a neutral bus bar, which is also grounded by a cable that's connected to either a metal water pipe or a rod driven deep into the earth. The two incoming 120-volt wires are connected to a main circuit breaker, which provides system protection by tripping open

in case of a fault and can be opened manually to shut off power to the entire home for maintenance or repair.

- ▶ From the main breaker, the two hot wires connect to these two main buses. And just as the buses at a substation distribute incoming power to multiple distribution feeders, the buses in your service panel distribute power to multiple circuits, each with its own circuit breaker. These breakers are arranged in two columns and mounted such that vertically adjacent breakers are on different buses.
- ▶ Standard 120-volt circuits, which power your lighting fixtures and most outlets and appliances, always consist of three wires: a hot wire, with black insulation, connected to one bus through a circuit breaker; a neutral wire, with white insulation, connected to the neutral bus; and a ground wire, either green or bare copper, also connected to the neutral bus. The three wires are bundled together inside a protective sheath.
- ▶ Standard 240-volt circuits, which power your clothes dryer, electric stove, and perhaps other heavy-duty appliances, always use four wires: hot, neutral, and ground (just like a 120-volt circuit), plus a second hot wire, with red insulation, connected to the other bus through the adjacent circuit breaker. Because the two hot wires are connected to different buses, there is a 240-volt difference between them—and, thus, the circuit can be used to power 240-volt appliances.

TERMS

bus: (1) In electrical power distribution, a set of electrical conductors used to route power through a substation. (2) In a communications satellite, the equipment responsible for transporting the mission payload into orbit and providing electrical power, attitude control, temperature control, and orbital adjustments.

bushing: In electrical power transmission and distribution, an insulated fitting that allows a high-voltage conductor to pass through a grounded metal case without causing a flashover.

circuit breaker: A switch that interrupts electric current in a conductor, either for maintenance or to prevent damage to the system in the event of a short circuit or other abnormal event.

fault: Any abnormal electric current.

flashover: An electrical phenomenon caused by a large voltage difference between two closely spaced conductors. If the voltage difference is large enough to overcome the electrical resistance of the air between the two conductors, current—in the form of a white-hot electrical arc—jumps the gap between them.

fuse: A device that interrupts electric current in a conductor to prevent damage to the system in the event of a short circuit or other abnormal event. Unlike a circuit breaker, a fuse cannot be operated manually and must be replaced after it has operated once.

insulator: A material or object that prevents the flow of electric current.

lightning arrester: In an electrical transmission or distribution system, a device that protects sensitive equipment by routing the power surge caused by a lightning strike into the ground.

neutral: An electrical conductor that provides a return path to complete a circuit.

recloser: A circuit breaker that that can automatically reclose the circuit after it has been opened due to a short circuit or other abnormal condition.

service drop: An electrical line that carries power into a building.

shield wire: A wire suspended above electrical power transmission lines to protect against lightning strikes.

short circuit: An electrical fault in which the current bypasses the normal load.

switch: In a telecommunications network, a computer that is used to establish and manage connections between transmission lines. Switches are located at nodes in a circuit-switched network.

voltage regulator: A device that makes minor adjustments to output voltage at an electric substation.

weatherhead: A fitting at which an electrical service drop enters a building.

READINGS

Blume, *Electric Power System Basics*, chapters 5 and 7.

Hayes, *Infrastructure*, chapter 5.

Wing, *The Visual Handbook of Building and Remodeling*, chapter 12.

QUESTIONS

- 1 Is power distribution to your home above ground or below ground?
- 2 Can you locate the substation that serves your neighborhood?

Everyday Thermodynamics: Refrigeration

LECTURE

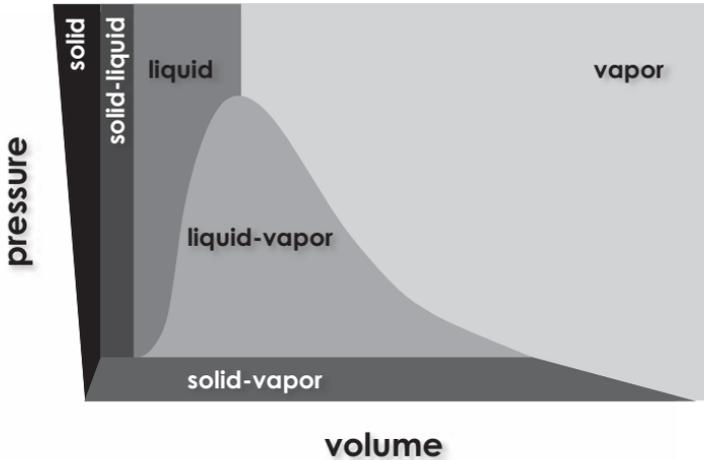
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In this lecture, you will learn about various everyday technologies that consume electrical power once it has reached your home. One of the most important of these technologies is refrigeration, which underlies not only your refrigerator, but also your air conditioner, and possibly even your heating system. Together, refrigeration and air-conditioning—both of which are thermodynamic processes—account for nearly 30% of the electrical power consumed in the average American residence.

Thermodynamics

- ▶ Thermodynamics is a branch of physics that's concerned with the relationships between heat, temperature, work, and energy. In thermodynamics, a fixed quantity of matter contained within a well-defined boundary is called a **system**. In classical thermodynamics, the state of a system is defined in terms of its properties—characteristics that can be measured and expressed quantitatively for the system as a whole at a given point in time, such as mass, volume, pressure, temperature, and internal energy.
- ▶ If the properties are unchanging, the system is said to be in **equilibrium**. It will remain in this equilibrium state until energy is transferred into or out of the system, at which point the properties will gradually change until a new equilibrium state is reached.
- ▶ There are only two forms of energy transfer: work and heat. Work is energy transfer associated with a force moving through a distance. Heat is energy transfer that occurs because of a temperature difference between two bodies or regions. Heat can move spontaneously in only one direction—from hot to cold—and as heat transfer occurs, the hot region gets cooler and the cold region gets warmer.

pressure-volume diagram



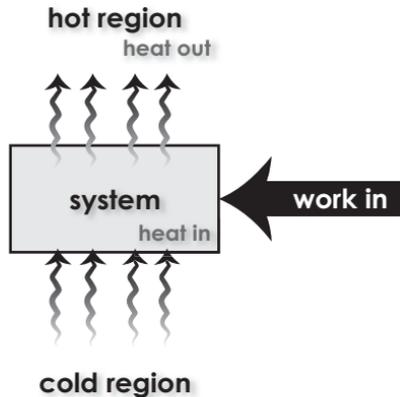
- ▶ When energy transfer causes a thermodynamic system to change from one equilibrium state to another, we say that a thermodynamic process has occurred. And we can visualize and understand such processes more clearly by using a graphical tool called the **pressure-volume diagram**. Each substance has its own characteristic pressure-volume diagram. In reference books, we can find them for water, ammonia, propane, and many other substances that are commonly used in thermodynamic processes.
- ▶ The pressure-volume diagram is not a standard line graph; rather, it's a graphical tool that allows us to characterize a substance at every possible equilibrium state. The tool has two fundamental characteristics: Any point plotted on the diagram represents a unique equilibrium state for the substance, and any line plotted on the diagram represents a thermodynamic process.

- ▶ A thermodynamic process is a transition from one equilibrium state to another, caused by a transfer of energy into or out of the system. We can control the direction of the thermodynamic process through various external mechanisms.
- ▶ Within the range of pressures we'll be dealing with in refrigeration, a change in phase from liquid to vapor entails a gradual transition across the **vapor dome**—from **saturated liquid** to **saturated vapor**—driven by energy input from outside the system.

Refrigeration

- ▶ Throughout much of human history, refrigeration has been achieved by harvesting naturally occurring ice and using it to cool beverages and preserve food. By the mid-19th century, this practice had become institutionalized through a wide-ranging infrastructure system that included industrial-scale harvesting of ice, an extensive transportation network, and local refrigeration provided by specially designed iceboxes in commercial facilities and private homes.
- ▶ Refrigeration with ice is a one-way thermodynamic process. Heat can move in only one direction: from hot to cold. Thus, in an old-fashioned icebox, heat is continuously transferred from the refrigerated space (which always has a temperature somewhat above freezing) to the ice. As heat is transferred from the refrigerated space, the temperature of that space falls, and as this same thermal energy is transferred into the ice, the ice melts. At some point, the ice will have melted away and must be replaced to begin the one-way process anew.
- ▶ The great technological revolution that ultimately produced modern refrigeration began in the early 1800s, when a succession of inventors and entrepreneurs developed a way to achieve cooling—not through a one-way process but, rather, through a cycle. In thermodynamics, a **cycle** is defined as a sequence of processes that begins and ends at the same state.

vapor-compression refrigeration



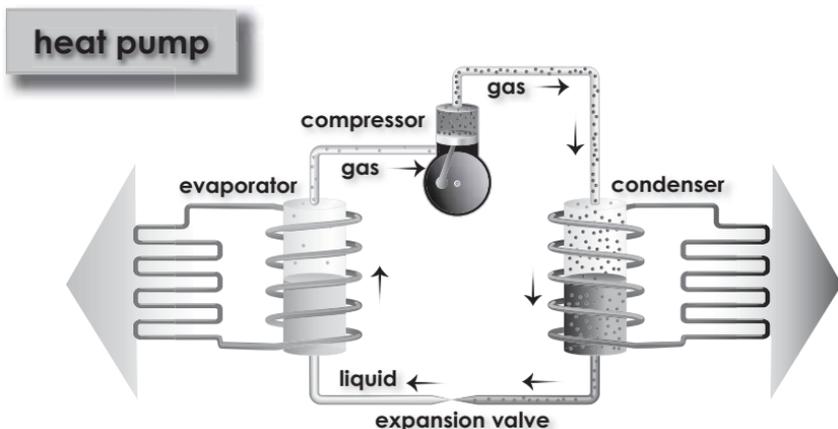
- ▶ The type of thermodynamic cycle used in nearly all modern refrigerators and air conditioners is called **vapor-compression refrigeration**. The thermodynamic system is a fixed quantity of fluid, called a **refrigerant**. The cold region is the refrigerated space, and the hot region is the external environment surrounding the refrigerator. Heat is transferred from the cold region into the refrigerant and then from the refrigerant into the hot region. The only way heat can move in this unnatural way—from cold to hot—is with additional energy input, in the form of mechanical work.
- ▶ In the mid-19th century, the earliest commercially successful vapor-compression refrigeration devices used waterpower as their source of mechanical energy, and because waterpower is both capital intensive and limited to locations along fast-moving rivers or streams, these early refrigeration devices were only suitable for use in large-scale industrial facilities, such as breweries, meat-packing houses, and ice-manufacturing plants.

- ▶ From a practical perspective, refrigeration couldn't enter the world of everyday engineering until electrical power became widely available in private homes during the first decades of the 20th century. Indeed, it wasn't until 1927 that General Electric sold the world's first mass-market electric refrigerator—called the Monitor Top—and even then, the technology wasn't quite ready for prime time, because the only available refrigerants were hazardous chemicals, such as ammonia, methyl chloride, and sulfur dioxide.
- ▶ The residential refrigerator didn't come of age until three years later, when Frigidaire, one of GE's competitors, invented a new synthetic refrigerant, dichlorodifluoromethane, which we now call Freon 12. Not only was this refrigerant safer than its predecessors, but it also had better thermodynamic qualities and thus facilitated the development of smaller, lighter, and cheaper refrigerators. The most important of these thermodynamic qualities is a boiling point somewhat below the intended temperature of the refrigerated space.
- ▶ Today, Freon 12 is recognized as a serious environmental hazard, but it's important to recognize that, at the time of its development, it was a game-changing invention that greatly improved the lives of many people.
- ▶ The key to successful implementation of vapor-compression refrigeration is the refrigerant itself, which must have just the right thermodynamic characteristics—most importantly, a boiling point somewhat below the intended temperature of the refrigerated space. The refrigerant also should be nonflammable, nontoxic, noncorrosive, and environmentally safe.
- ▶ Freon 12 is classified as a chlorofluorocarbon (CFC), and in the 1970s, scientists discovered that CFCs have been accumulating in Earth's upper atmosphere, where they react with and deplete the atmospheric ozone layer that protects us from excessive solar ultraviolet radiation. As a result, the use of CFCs was curtailed by an international agreement—the Montreal Protocol of 1987—and in the United States, Freon 12 was banned by the Clean Air Act of 1990.

- ▶ Suitable replacements were quickly developed and incorporated into refrigeration and air-conditioning systems worldwide. These substances—such as R-134a for automotive air-conditioning systems and R-410a for residential systems—have thermodynamic properties similar to Freon 12 but no potential for ozone depletion.
- ▶ Unfortunately, both R-134a and R-410a were recently found to be potentially significant contributors to climate change. R-134a has already been banned from use in the European Union, and additional restrictions on both substances are likely. So, the pursuit of environmentally safe refrigeration, which began in the 1920s, continues today.

Air-Conditioning

- ▶ Both refrigeration and air-conditioning use the same thermodynamic cycle and the same major components. The only substantive difference between an air conditioner and a refrigerator is the physical arrangements of the hot and cold regions on which the thermodynamic cycle is based. For refrigeration, the cold region is the refrigerated space, and the hot region is your kitchen. In air-conditioning, the cold region is the interior of your home, and the hot region is the outside air.



- ▶ One of the most interesting aspects of vapor-compression technology is that it can be used for heating as well as cooling. When the vapor-compression cycle is used for heating, it's called a **heat pump**. Like an air conditioner, the heat pump is designed to move heat from a cold region to a warm region, using mechanical work input to drive the cycle. The only difference between these two devices is their purpose.
- ▶ The purpose of refrigeration is to remove heat from a cold region, while the accompanying transfer of heat into the warm region is merely a by-product of the thermodynamic cycle.
- ▶ The purpose of a heat pump is to add heat to a warm region, while the removal of heat from the cold region is now the by-product. To accomplish this alternative purpose, the heat pump is essentially an air conditioner that's been turned inside out.

TERMS

cycle: (1) In thermodynamics, a sequence of processes that begins and ends at the same state. (2) In traffic engineering, the total period of time, in seconds, required for a signal light to repeat its programmed green-yellow-red sequence in all directions.

equilibrium: (1) In mechanics, the condition in which all forces acting on a body or system are in balance. Mathematically, for a body in equilibrium, the vector sum of all forces acting on the body equals zero. (2) In thermodynamics, the condition in which all properties of a system are unchanging.

heat pump: A device that uses the vapor-compression refrigeration cycle to heat an enclosed space.

pressure-volume diagram: In thermodynamics, a graphical representation of equilibrium states or thermodynamic processes in terms of pressure, volume, and temperature.

refrigerant: A fluid used to facilitate the transfer of heat in the vapor-compression refrigeration cycle.

saturated liquid: The thermodynamic state at which a fluid has just begun to boil but is still 100% liquid.

saturated vapor: The thermodynamic state at which a fluid is at its boiling point and is 100% vapor.

system: In thermodynamics, a fixed quantity of matter contained within a well-defined boundary.

vapor-compression refrigeration: The thermodynamic cycle that serves as the basis for most modern refrigeration.

vapor dome: On a pressure-volume diagram, the dome-shaped transition region between the liquid and vapor phases.

READINGS

Moran, Shapiro, Boettner, and Bailey, *Fundamentals of Engineering Thermodynamics*.

Wing, *The Visual Handbook of Building and Remodeling*, chapter 17.

QUESTIONS

- 1 Why is it important to keep your refrigerator's condenser coils clean?
- 2 Why does it make sense to allow a bowl of hot leftovers to cool to room temperature before putting it into the refrigerator?

Your home is an integrated assemblage of eight major engineered subsystems. Thus far, you have learned about six of these subsystems: structural, foundation, building envelope, site, plumbing, and electrical. In this lecture, you will examine the seventh: heating, ventilating, and air-conditioning (HVAC). This lecture will focus primarily on heating systems and on the integration of heating with air-conditioning technologies, leaving ventilation for next lecture, in conjunction with a broader discussion of energy efficiency in residential construction.

Residential Heating

- ▶ A residential heating system consists of three major components: a device for converting chemical or electrical energy into heat; a means of distributing that heat throughout the building; and a mechanism for controlling the system, such that the desired temperature is maintained. If the building is cooled as well as heated, then an air-conditioning system also might be integrated with the heating system.
- ▶ A thermostat is used to control your home's inside temperature. This is a simple yet vitally important technology, not only for home heating, but also for temperature control in your refrigerator, oven, iron, and a host of other common devices, including your automobile.
- ▶ Every thermostat must have an element that's capable of sensing and responding to changes in temperature. In most thermostats, the design of this element is based on a natural phenomenon, the thermal expansion and contraction of materials.
- ▶ Heat is the spontaneous transfer of energy from a hot region to a cold region. Heat transfer can occur in any of three different modes: **conduction**, **thermal radiation**, and **convection**.

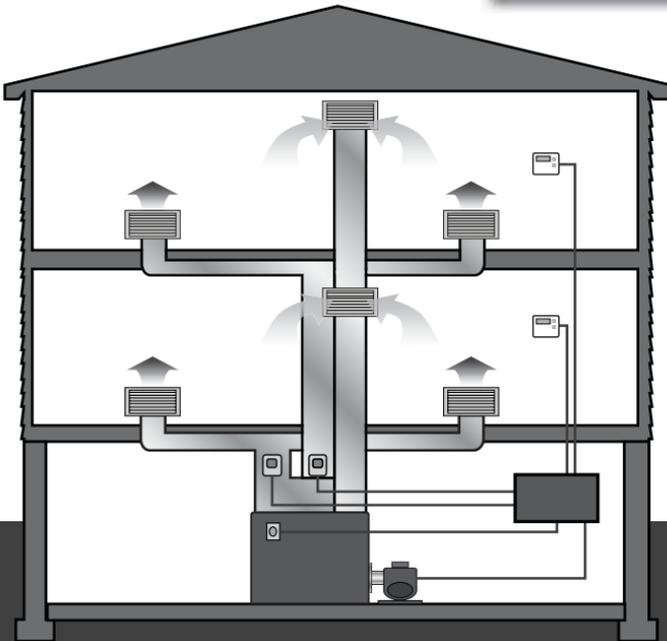
- Conduction is heat transfer through a substance or through physical contact between substances.
- Thermal radiation is heat transfer through electromagnetic waves emitted by a substance. Unlike conduction, radiation doesn't require an intervening medium for transmission. It can even move through a vacuum.
- Convection is heat transfer through the movement of a liquid or gas. There are two types: Natural convection is fluid movement caused by differences in density—such as hot air rising through a chimney—while forced convection is externally driven—for example, by a pump or a fan.

The Furnace

- ▶ There are three principal types of modern whole-house residential heating: the furnace, with heat distributed by forced air; the boiler, with heat distributed by circulating water; and the heat pump, usually with forced-air distribution, as well.
- ▶ The furnace with forced-air distribution is the most common heating system used in North America. The furnace can be fueled by natural gas, propane, or heating oil. A gas furnace has four main components: the burner, electric **blower**, heat exchanger, and control system.
- ▶ When your thermostat calls for heat, the control system opens a valve, sending gas to the burner, where it's ignited by a pilot light. Outside air is drawn by natural convection through an intake pipe to provide oxygen for combustion. The resulting hot combustion gases flow upward through the heat exchanger and are then exhausted through a stack that extends out through the roof or a wall.

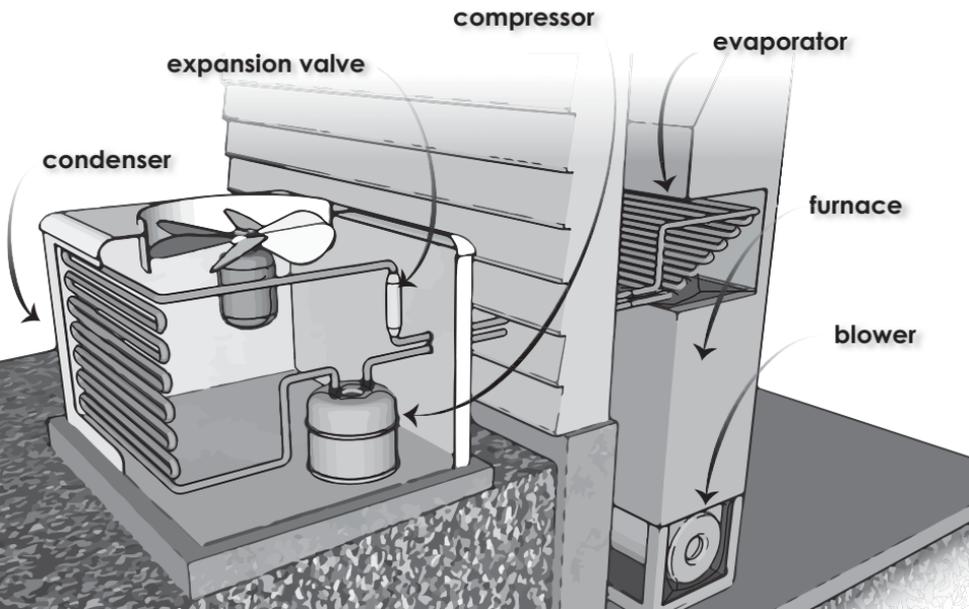
- ▶ Meanwhile, once the burner is going strong, the blower switches on, drawing air from the main return duct, through a filter, and then up through the heat exchanger, where it's heated by the exhaust gases rising from the burner. This stream of hot air is then propelled by the blower into the main supply duct, called a **plenum**.
- ▶ Two separate streams of air are moving through the furnace: combustion air, which originates outside the house, feeds the flame, and then is exhausted through the stack; and circulating air, which originates from, and returns to, the home's occupied spaces. The heat exchanger's job is to transfer heat from one stream to the other without allowing any intermixing—so that those noxious combustion fumes won't contaminate the air we breathe. This heat transfer occurs primarily by conduction through the heat exchanger's metal walls.

forced-air distribution



- ▶ Two energy inputs—the combustion of fossil fuel and the electricity required to spin the blower—produce a steady stream of hot air, which is propelled by the blower through supply ducts into individual rooms. This is heat transfer by forced convection.
- ▶ In many homes, the distribution ducts are partitioned into two or more zones, each with its own thermostat, so that different areas of the house can be maintained at different temperatures. The flow of hot air into each zone is regulated by a **damper**, which is controlled by signals from a zone control panel.
- ▶ Supplying an adequate quantity of warm air to your home's occupied spaces is only half of the distribution system's job. To maintain proper circulation, an equal quantity of air must be pulled back to the furnace through a parallel set of return ducts, again propelled by the blower. At the point where each supply and return duct penetrates an interior wall, there's an adjustable vent called a **register**, which allows you to control the flow of air into and out of each heated space.

split system



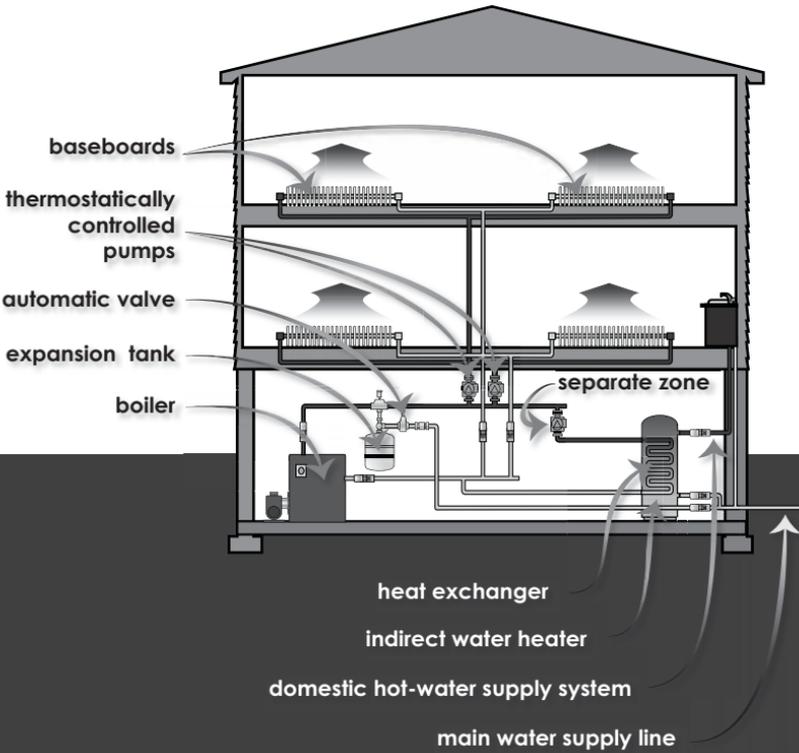
- ▶ A common problem with forced-air heating systems is their susceptibility to air-pressure imbalances. The key to avoiding pressure imbalances is ensuring that the quantity of warm air supplied to each heated space is equal to the quantity of return air pulled from it.
- ▶ Another common complaint about forced-air systems is that they produce excessively dry interior air. An effective remedy is to install a whole-house humidifier, which attaches directly to your main supply plenum and adds moisture to the circulating air.
- ▶ Forced-air heating is popular in the United States because, in these systems, a single system of ductwork can be used for heating, cooling, air filtering, and humidification, an efficiency that greatly simplifies installation and thus saves money.
- ▶ In a standard central air conditioner, called a split system, the compressor, condenser, and **expansion valve** are located in a standalone unit outside, while the **evaporator** is indoors. In an integrated system, the evaporator is placed inside the supply plenum, just above the furnace. Thus, when the air-conditioning system is operating, cool air is circulated through the same ducts used by the heating system and is propelled by the same blower. It's a very efficient setup that accounts, in large measure, for the popularity of forced-air heating systems in climates that require both heating and air-conditioning.

The Boiler

- ▶ The boiler with hot-water distribution, also called **hydronic heating**, is the type of heating system that is common in Europe and was common in the United States until widespread adoption of central air-conditioning prompted the shift to forced-air systems. Today, it's staging a comeback in the United States, thanks to the growing popularity of **radiant floor heating**.

- ▶ At the heart of every hydronic heating system is a boiler, fueled by natural gas, propane, or heating oil. The boiler works just like the furnace in a forced-air system—except that water, rather than air, circulates through the heat exchanger and the distribution system. The pipes of the distribution system are arranged in closed loops—one per zone—with water circulated by one thermostatically controlled pump for each loop. In the occupied spaces, radiators or baseboards are used to transfer heat to the surrounding air, primarily by natural convection.

hydronic heating system



- ▶ There are three other unique aspects of hydronic heating systems.
 - Because water in the closed distribution loops expands as it heats, the system includes an expansion tank to accommodate the water's changing volume.
 - To compensate for leaks and evaporation, the system is connected to the home's main water supply line, with in-flow controlled by an automatic valve.
 - Unlike forced-air heating, hydronic heating can be integrated with the domestic hot-water supply system.
- ▶ Hydronic heating has a number of advantages over forced-air heating. From the builder's perspective, the small-diameter water pipes are much easier to route through walls than large ducts, and it's somewhat easier to configure and control separate zones in a hydronic system. From the occupant's perspective, hydronic systems produce more even distribution of heat, and they don't cause air-pressure imbalances.
- ▶ On the negative side, hydronic heating is generally less responsive than forced-air heating. There's also the danger of water damage due to leaking pipes. And while hydronic cooling is now commonplace in Europe, it's still not widely available in the United States, so separate ductwork is typically required for air-conditioning.

The Heat Pump

- ▶ The heat pump is essentially an air conditioner that's been turned inside out. In an air conditioner, the condenser, which transfers heat from the refrigerant into the warm region, must be oriented toward the exterior of the house. But in a heat pump, the condenser is oriented toward the interior. Similarly, the evaporator, which transfers heat from the cold region to the refrigerant, is oriented toward the interior in an air conditioner, but toward the exterior in a heat pump. Otherwise, heat pumps and air conditioners operate in the same way.

- ▶ A great advantage of this technology is that one system can be used for both heating and cooling, an arrangement that can save both installation cost and space. Both the heat pump and air conditioner are heat exchangers. Each is just a copper coil with a fan blowing across it. Thus, in a combined heat pump–air conditioner, each coil can be used as either a condenser or an evaporator, and the only mechanical action required to switch between cooling and heating is to reverse the direction of the refrigerant flow. This is accomplished with the aid of a few cleverly designed valves.
- ▶ Heat pump systems have the added advantage of using one set of ducts for heating, cooling, humidification, and air filtering. Modern heat pumps also have very high thermodynamic efficiency. For these reasons, in moderate climates requiring both heating and air-conditioning, a heat pump can be cost effective.
- ▶ Like all engineered systems, the heat pump also has some significant performance limitations. Most importantly, its heating performance drops off sharply when the outside air temperature dips below 30°F. When a heat pump is used in a cold climate, the system usually includes supplemental electrical-resistance heating, which tends to be very expensive.
- ▶ The rapidly increasing popularity of a technology called the ground-source (or geothermal) heat pump is being driven primarily by growing interest in energy efficiency. This device uses the earth, rather than the outside air, as its heat source in the winter and its heat sink in the summer. This technology exploits a simple geophysical phenomenon: The underground temperature of the earth is lower than the air temperature in the summer and higher than the air temperature in the winter.
- ▶ Ground-source heating and cooling is expensive to install, and its effectiveness is strongly influenced by the type and moisture content of the soil. These limitations notwithstanding, the ground-source heat pump is among the most economical and environmentally friendly options for whole-house heating currently available.

TERMS

blower: A centrifugal fan.

conduction: Heat transfer through a substance or through physical contact between substances.

convection: Heat transfer through the movement of a liquid or gas.

damper: A valve or gate that controls the flow of air through a conduit.

evaporator: A device that changes a liquid to a vapor by transferring heat into the fluid.

expansion valve: A device that reduces the pressure of a fluid.

hydronic heating: A heating system that operates by circulating hot water from a boiler throughout the heated space.

plenum: The main air supply duct in a forced-air heating system.

radiant floor heating: A hydronic heating system in which hot water is circulated through the floor of a building.

register: A grill with shutters for controlling the flow of air in a heating or air-conditioning system.

thermal radiation: Heat transfer through electromagnetic waves emitted by a substance.

READINGS

Johnston and Gibson, *Green from the Ground Up*, chapter 9.

Wing, *The Visual Handbook of Building and Remodeling*, chapters 16 and 17.

QUESTIONS

- 1 What type of HVAC system does your home use? Based on this lecture, do you consider it to be an optimum choice? If not, what type of system would be better?
- 2 Why is electrical resistance heating so expensive?

Home Energy Efficiency

In this lecture, you will explore one of the most important trends in modern residential construction: the green building movement, which advocates the design and construction of buildings that use natural resources more efficiently while minimizing adverse impacts on our environment. Green building is a broad, holistic approach that seeks to minimize energy consumption, maximize the use of renewable and recycled materials, minimize water consumption, minimize or eliminate emissions, improve indoor air quality, and reduce waste. This lecture will focus on the most important dimension of green building: minimizing energy consumption.

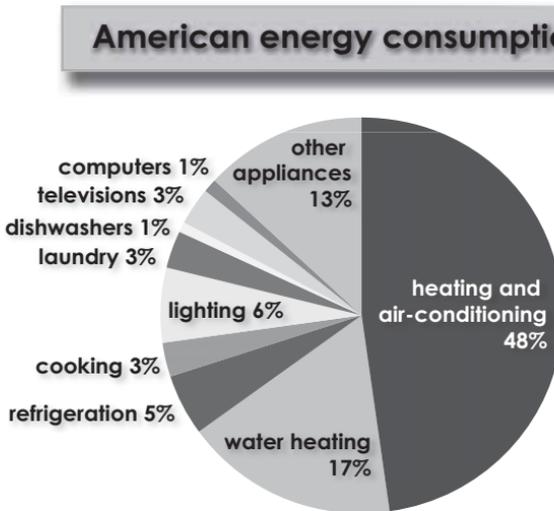
The Green Building Movement

- ▶ The trend toward increased energy efficiency has been underway at least since the energy crisis of the 1970s, and the green building movement has gained considerable momentum in the past decade as governments, industry groups, professional societies, and the public have become increasingly aware of both the environmental and economic benefits of sustainable development.
- ▶ During this period, governments at all levels have established incentive programs for green construction; professional organizations have established technical standards and certification programs; successive editions of the International Residential Code have added progressively more stringent provisions for energy efficiency, while also accommodating new green building technologies; the emerging field of **building science** has provided much-needed research to support these new developments; and consumers, in increasing numbers, have begun demanding greener homes.

- ▶ In the United States, the residential sector accounts for 22% of total energy consumption and 37% of electrical power consumption. Thus, even modest gains in residential energy efficiency can make a substantial difference in our overall energy picture. And achieving modest gains is neither difficult nor expensive, particularly for new construction.

Insulation

- ▶ An energy-efficient home has five minimum essential characteristics: a well-insulated building envelope, to minimize heat transfer; a well-sealed building envelope, to minimize air infiltration; energy-efficient windows and doors; an energy-efficient heating, ventilating, and air-conditioning (HVAC) system; and energy-efficient appliances. By far, heating and air-conditioning account for the largest share of residential energy consumption, and that's why four of the five characteristics of energy-efficient construction are focused in this area.



- ▶ Insulation is a construction material that's used primarily to reduce heat transfer by conduction. **Thermal resistance** is the extent to which a particular material resists the movement of heat through it, and it is expressed quantitatively using a number called the **R-value**.

- ▶ The 2015 International Residential Code requires that all exterior walls have a minimum of R-13 in the southern United States and R-20 or higher elsewhere. Moreover, many green building advocates suggest that R-20 is inadequate and that R-24 or even R-30 wall insulation is necessary for optimum energy efficiency. In the years ahead, it's likely that the codes will continue moving in this direction.

- ▶ Today, builders are addressing this challenge in a variety of creative ways. One approach is simply to use higher-performing insulation, such as urethane foam, within the wall cavities. A more robust approach is adding rigid foam insulation to the outside of the wall, and other types of insulation can still be placed inside the cavity to further increase the wall's R-value.

- ▶ The most revolutionary approach to increasing the wall's thermal resistance can be seen in recent initiatives to reengineer the wall itself. One such approach, called **advanced framing**, alters the most fundamental standard of traditional platform framing by replacing 2-by-4



studs spaced 16 inches apart with 2-by-6 studs spaced 24 inches apart, reducing the total required quantity of lumber by about 25%.

- ▶ Perhaps the most effective approach is to eliminate wall framing altogether by using a technology called the **structural insulated panel (SIP)**, which consists of two structural boards—typically oriented strand board—bonded to a solid foam core, with total thickness ranging from 4.5 to 12.25 inches, depending on the required R-value.
- ▶ SIPs serve as both structure and insulation. They can be used for walls, roofs, and floors. Because they have so few joints, houses made of SIPs are considerably more airtight than their platform-framed neighbors. SIPs are always custom fabricated in the factory or shop, so they can be erected quickly on site with a small crew and a crane. And as soon as the structural shell is up, the builders have a fully enclosed, insulated space in which to continue their interior work.
- ▶ Like all technologies, SIPs have their drawbacks. Their fire resistance and sound **attenuation** are reported to be somewhat lower than conventional framing. At present, the up-front cost of building with SIPs can be somewhat higher than the cost of conventional framing, though the cost gap is narrowing as SIPs become more widely used. And when energy savings are taken into account, the life-cycle cost of building with SIPs is typically 40% lower than that of framed construction. Its shortcomings notwithstanding, the SIP is a very impressive technology that's likely to see more widespread use in the future.

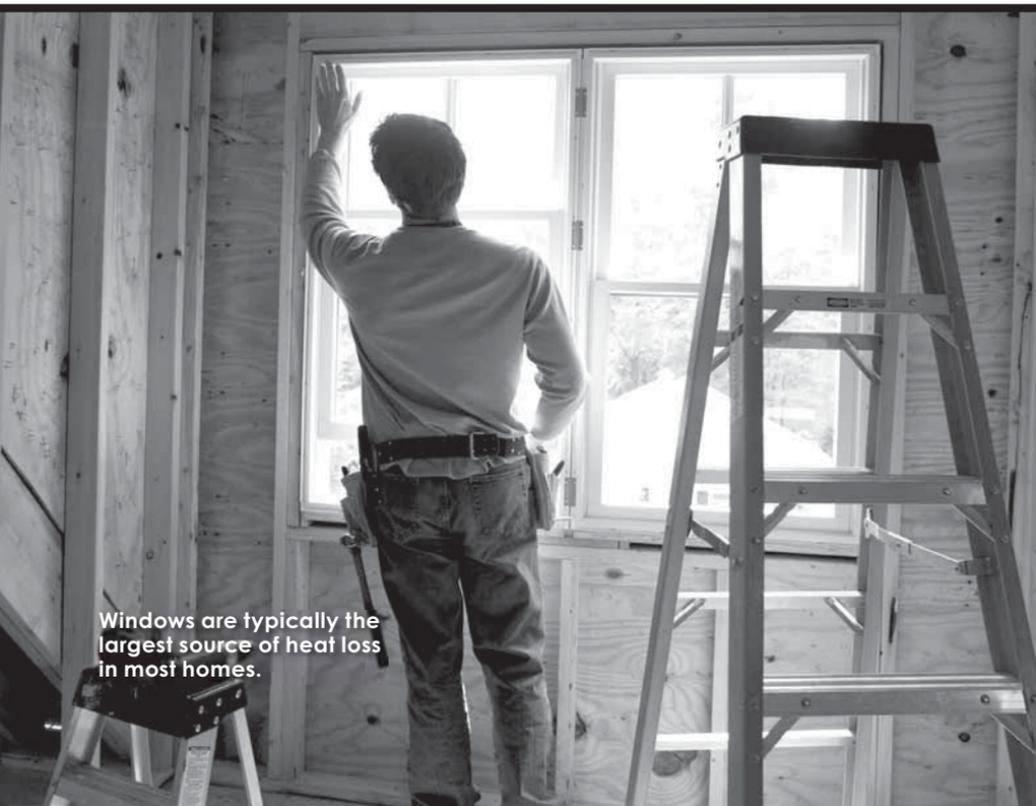
Minimizing Air Infiltration

- ▶ No matter how well insulated your building envelope might be, its energy efficiency can be compromised by air infiltration, which can cause heat losses of up to 40%. The principal purpose of insulation is to resist heat transfer by conduction, but heat can also move by convection, and many insulations do little to prevent convection.

- ▶ Air infiltration is driven by three different physical phenomena.
 - Wind blowing across your house creates high pressure on the upwind wall and low pressure on the downwind wall. The air pressure inside your house lies somewhere between these two extremes. Because air naturally moves from high pressure to low pressure, the imbalance between outside and inside causes air to infiltrate from outside to inside on the upwind wall and from inside to outside on the downwind wall.
 - Forced-air heating systems can cause similar pressure imbalances and similar movements of air through the building envelope.
 - Within your home, hot air rises and eventually finds its way into the unheated attic space, and as the warm air escapes from the top of the building envelope, cold air seeps in somewhere below to replace it.
- ▶ Given these causes, minimizing air infiltration is simple in concept but challenging in practice. The building envelope should include a well-defined air barrier, typically consisting of exterior housewrap or rigid-foam insulation, interior spray-foam insulation, or well-sealed interior drywall.
- ▶ The inevitable penetrations through the air barrier—for example, at vents and outdoor faucets, outlets, and light fixtures—must be thoroughly sealed with caulk or sealant. Air leaks are also common at the intersections between different materials, and these must be caulked, as well.
- ▶ Finding every possible leak in the building envelope would be impossible if it weren't for the blower door, which identifies gaps in the air barrier. When used on a completed house, the blower-door test can provide valuable information for an energy audit, but it's even more valuable before the interior drywall has been installed, when leaks can be more easily sealed.

Windows and Doors

- ▶ Windows represent a special challenge, because they create discontinuities in both the insulation and the air barrier. As a result, windows are typically the largest source of heat loss in most homes. Modern energy-efficient windows respond to this challenge by purposefully addressing each possible mode of heat transfer: conduction, radiation, and convection.
- ▶ With respect to conduction, a single pane of glass has a thermal resistance of R-1—not quite as bad as a hole in the wall, but very close. And that’s why energy-efficient windows have at least two panes of glass, with a buffer of stagnant air in between. A double-glazed window achieves at least R-2, as long as the gap between panes is at least half of an inch.



Windows are typically the largest source of heat loss in most homes.

- ▶ But heat can still move across that gap by convection, so the gap is typically filled with a heavy gas, such as argon, to reduce convective losses. To limit heat transfer by radiation, high-performance windows use **low-emissive coatings**, which reflect radiant heat back to the side of the glass where it originated while allowing visible light to pass.
- ▶ These so-called low-e windows achieve at least R-3, but with the addition of a third pane of glass and multiple low-e coatings, a new breed of super windows is now able to achieve R-values in excess of 10. These windows aren't cheap, but having windows with thermal resistance comparable to that of a solid wall takes green building to a whole new level.
- ▶ When you go shopping for windows, look for a label bearing the official certification of the National Fenestration Rating Council. The most important piece of information on the label is a number called the **U-factor**, or thermal transmittance, which is just one divided by the R-value.

Ventilation

- ▶ Even though you've installed high-quality windows with low air leakage in a well-sealed building envelope, by minimizing air infiltration, you've almost certainly created a new problem: stale, unhealthy air. The air in your home can accumulate a wide variety of pollutants, such as dust and hazardous gases, as well as moisture, which can condense on cold surfaces or inside wall cavities, causing rot and mold.
- ▶ For these reasons, mechanical ventilation is essential for any modern energy-efficient home. The American Society of Heating, Refrigerating and Air-Conditioning Engineers sets the standard for residential ventilation: 35% of your inside air should be replaced with fresh outside air every hour.
- ▶ However, bringing large quantities of outside air into an energy-efficient house seems counterproductive. Why have we invested so much in

sealants and insulation only to undo our own efforts by pulling cold outside air into the heated interior space in the winter, or vice versa in the summer?

- ▶ The answer to this quandary is a **heat recovery ventilator (HRV)**, a combination ventilation system and heat exchanger. The best HRVs can transfer up to 85% of the heat from the warm airstream to the cool one, thus achieving significantly better energy efficiency than the alternative forms of ventilation—an open window or a leaky building envelope.

HVAC Equipment

- ▶ The most important aspect of efficiency in HVAC systems is getting the size right. HVAC systems can waste a lot of energy if they have too little capacity or too much capacity. Your HVAC professional can determine the required system capacity based on a calculation of the total heating and cooling loads for your house.
- ▶ But don't forget that the heating and cooling loads will be substantially reduced by improved insulation and sealing and by high-performance windows and doors, so it's essential that these enhancements to the building envelope be planned or implemented before the capacity of the HVAC system is determined. If not, you'll probably be buying more capacity than you really need.

Appliances

- ▶ Selecting energy-efficient heating and air-conditioning systems can produce large residential energy savings, but choosing energy-efficient appliances can produce even greater savings. The challenge is that there is a very large number of appliances, and making smart choices for all of them can seem like a daunting task.

- ▶ Fortunately, this task has been greatly simplified by the Energy Star program, a joint initiative of the U.S. Department of Energy and the Environmental Protection Agency. This program sets strict standards for energy efficiency, so Energy Star-rated appliances typically use 20% to 30% less energy than their nonrated counterparts.

TERMS

advanced framing: An adaptation of the traditional platform-framing method for residential construction. Advanced framing provides better energy efficiency, better sustainability, and lower cost.

attenuation: In telecommunications, the tendency of a transmitted signal to become weaker with increasing distance traveled.

heat recovery ventilator (HRV): A ventilation device that improves energy efficiency by transferring heat between the incoming and outgoing airstreams.

low-emissive coating: A coating applied to energy-efficient windows to limit heat transfer by radiation.

R-value: A quantitative measure of thermal resistance.

structural insulated panel (SIP): A recently developed technology for highly energy-efficient residential construction. A SIP serves as both structure and enclosure.

thermal resistance: The extent to which a particular material resists the movement of heat through it.

U-factor: Thermal transmittance. The U-factor is the mathematical reciprocal of the R-value.

READINGS

Johnston and Gibson, *Green from the Ground Up*.

Wing, *The Visual Handbook of Building and Remodeling*, chapter 13.

QUESTIONS

- 1 What are some challenges associated with improving energy efficiency in existing homes?
- 2 Why has fiberglass remained so popular for thermal insulation in the United States, even though so many superior products are now available?

Passive Solar and Net-Zero-Energy Homes

As effective as they might be, the basics of energy efficiency are really just incremental improvements over the old ways of reducing consumption—more insulation, better control of air infiltration, better windows, and more efficient appliances. But in this lecture, you're going to break with the past as you learn about a fundamentally new paradigm, called passive solar design, a more holistic approach that considers energy efficiency in many of the most fundamental decisions about a home's design.

Passive Solar Design

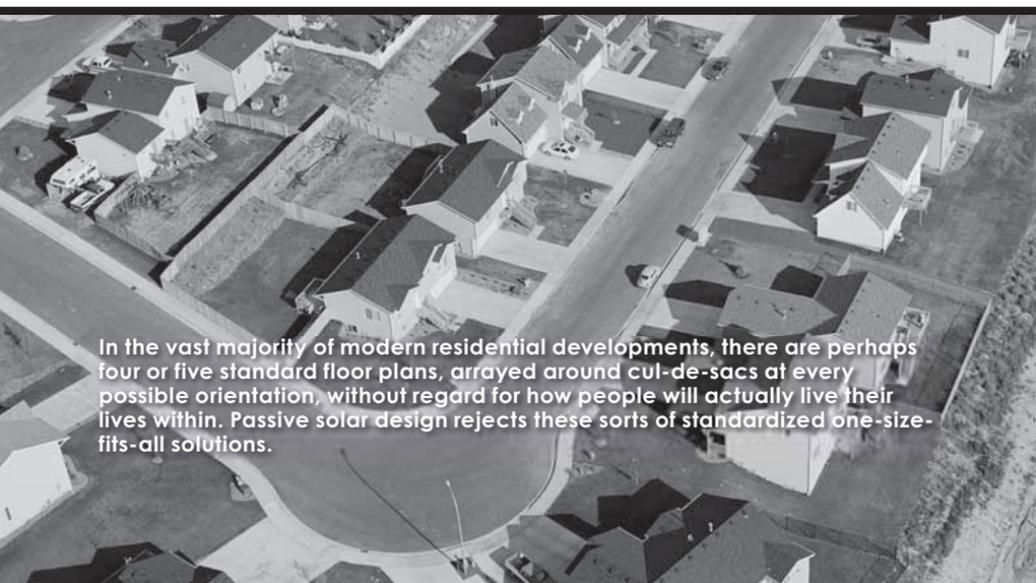
- ▶ The concept of **passive solar design** derives from a recognition that energy efficiency can be enhanced, not only by reducing consumption, but also by tapping into an abundant and readily available supply of free energy—the thermal radiation of the Sun.
- ▶ In passive solar design, a building's location, orientation, architectural configuration, and interior features are chosen, first and foremost, to maximize solar heat gain in the winter and to minimize it in the summer. This approach is characterized as passive because it employs no mechanical or electrical devices to harvest solar energy; a passive solar house merely uses the sunshine that falls on it in a variety of ingenious ways.
- ▶ We use many forms of solar energy, often without realizing it. There's photovoltaic power generation, of course, but in a broader sense, most other forms of power generation also depend on solar energy at the most fundamental level. Fossil fuels originated as plants and microorganisms that acquired their **biomass** through photosynthesis; hydroelectric power is dependent on the hydrologic cycle, which is powered by the Sun; and the wind that drives wind turbines is caused by differences in atmospheric pressure resulting from solar heating of the Earth. Passive solar uses solar energy directly—and, therefore, more efficiently.

- ▶ A passive solar home cuts out all the middlemen. The Sun's thermal radiation enters the house through windows; it impinges directly on floors, walls, and furniture; and about 70% of it is reradiated back into the room as heat. All of this heat is free.
- ▶ This process is called **direct solar heat gain**. The single most important principle of passive solar design is that the house should be oriented to maximize direct gain. In the Northern Hemisphere, the building should have one wall facing as closely as possible to the south, such that it receives maximum-possible exposure to the Sun. The long axis of the building should be oriented east to west, so that the southern wall is longer than the eastern or western walls. And there should be no trees, neighboring buildings, or terrain features that prevent winter sunlight from reaching this southern wall.
- ▶ To make the best use of direct gain, you've got to hold onto it—so the passive solar home must be extremely well insulated and airtight. Passive solar doesn't reject the basic methods of achieving energy efficiency; in fact, it demands that these methods be implemented to a very high standard.
- ▶ In passive solar design, no component of the building receives more attention than the windows. Windows are essential for achieving heat gain, but they're also the greatest source of heat losses. Thus, determining the required window area in a passive solar home is a delicate balancing act. If the window area is too small, direct gain in the winter will be inadequate; if it's too large, the house will overheat in the summer and lose too much heat in the winter.
- ▶ In heating climates—that is, in colder regions, where heating demands exceed air-conditioning demands—south-facing windows should be relatively large and numerous. The north-, east-, and west-facing walls should have only enough window area to provide adequate natural lighting. To minimize heat losses, all windows should have the lowest possible U-factor, but to properly control direct gain, the **solar heat gain coefficient** should be high for south-facing windows and low for all the others.

- ▶ In cooling climates—where air-conditioning demands exceed heating demands—north-facing windows should be larger and should be the preferential source of interior lighting. South-facing windows should be smaller and shaded (with roof overhangs or awnings) to prevent direct gain in the summer. And all windows should be rated for both low solar heat gain and low thermal transmittance.
- ▶ In passive solar design, the collection and storage of solar energy is usually localized. It all happens in the immediate vicinity of the south-facing windows. A significant challenge, then, is distributing this heat more-or-less evenly throughout the occupied space. This can be done with mechanical ventilation, but fans consume electrical power that we're trying to save, so it's preferable to use natural means to the greatest extent possible.
- ▶ To this end, the most successful passive solar homes typically use a relatively small footprint and an open interior plan to promote natural air circulation. In warm weather, natural cooling can be enhanced by positioning windows to achieve cross-ventilation and by using upper-level openings to exhaust naturally rising hot air.
- ▶ This latter phenomenon, called **stack ventilation**, is often promoted by incorporating a tower or split roof into the architectural design. When vents or windows on the highest level are open, hot air is constantly being flushed out, and cooler air is drawn in from below—preferably through vents located on the shadiest side of the house, perhaps a porch or shaded garden.
- ▶ Although the focus of passive solar design is on heating and cooling, a variety of other energy-saving measures are often incorporated into passive homes. These include using solar hot-water heaters and solar cookers; harvesting heat from wastewater; purposefully using refrigerators, computers, and other electronic devices as heat sources; and, perhaps most importantly, maximizing natural illumination.
- ▶ Electric lighting accounts for about 6% of power consumption in the average U.S. residence, and that 6% can be drastically reduced with

purposeful design for natural lighting—and wherever supplemental artificial lighting is still needed—by switching from power-hungry incandescent bulbs to highly efficiency light-emitting diode (LED) bulbs.

- ▶ The size, placement, and types of windows used in a passive solar house should be based on facilitating or preventing direct solar gain and on preventing heat loss. Given these constraints, it's generally not going to be possible to tailor the window configurations for optimized natural lighting.
- ▶ Rather, we need to look beyond the windows to the placement of individual rooms within the architectural floor plan. The concept is to consider the time of day when each interior space will be used most intensively and to position that space where the natural light will be optimal at that time. But there are no universal answers; the design can and should reflect the occupants' individual lifestyle and preferences.
- ▶ Passive solar design is truly holistic. No aspect of a passive solar design is exempt from being reinvented for the sake of improved building performance. When it's implemented well, the passive solar approach leads to individualized designs that are uniquely suited to their location, climate, and occupants' needs.



In the vast majority of modern residential developments, there are perhaps four or five standard floor plans, arrayed around cul-de-sacs at every possible orientation, without regard for how people will actually live their lives within. Passive solar design rejects these sorts of standardized one-size-fits-all solutions.

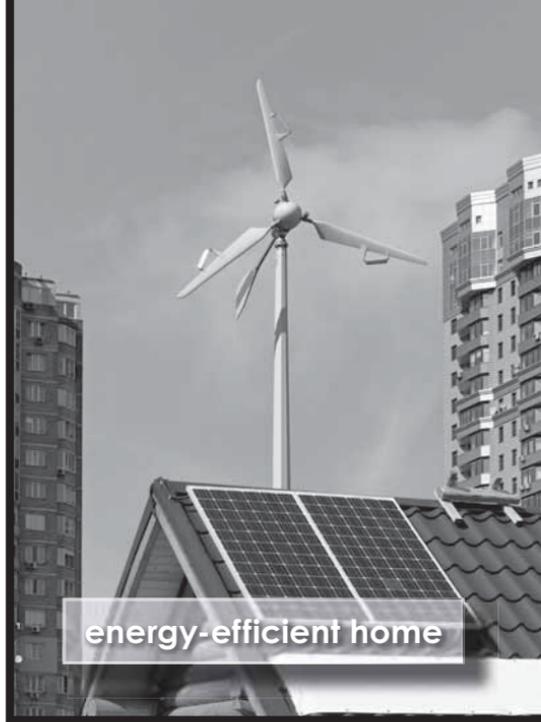
- ▶ How effective is this approach at achieving its primary purpose of reduced energy consumption? It depends on climate. For example, heating climates with relatively large diurnal temperature fluctuations are more likely to yield dramatic results than warm, humid climates.
- ▶ More importantly, it depends on the extent to which passive solar principles are actually implemented. In a moderate climate, with rigorous implementation and high-quality construction, it's possible for a passive solar home to require no mechanical heating or air-conditioning at all. Even in such cases, however, a small, supplemental heating appliance is typically included in the design for unexpectedly cold weather or emergencies.
- ▶ Just as the effectiveness of passive solar design depends on the extent and quality of implementation, so does its cost. Certainly, super windows and R-40 wall insulation can add significantly to the construction cost. But with the possibility of heating-load reductions exceeding 75%, it's only a matter of time before energy cost savings fully offset the additional construction costs.
- ▶ It's also important to recognize that many of the most essential features of passive solar design can be implemented at no additional cost. The house's orientation costs nothing. Getting the floor plan right costs nothing.

Net-Zero-Energy Homes

- ▶ Today, we're seeing an increasing number of homeowners and builders taking another big step forward, with the **net-zero-energy home**, a building that requires no net input of energy over the course of a year. Most net-zero homes aren't self-sufficient on a day-to-day basis; rather, they produce as much energy as they use on an annual basis.
- ▶ To achieve this outcome, they typically combine aggressive implementation of passive solar design principles with one or more active in-home renewable energy sources, such as photovoltaics, a wind

turbine, or geothermal power generation. These homes inevitably draw some electrical power from the grid—when demand is unusually high or when on-site power generation is low—but then they return an equal amount to the grid during periods when they're generating more energy than they consume.

- ▶ Net-zero design only makes sense if the electric utility offers net metering, the practice of giving credit (at the retail price) for consumer-generated power that's supplied to the grid. This is currently not an issue in the United States, since the Energy Policy Act of 2005 required all public utilities to offer net metering to their customers.



TERMS

biomass: A form of renewable energy obtained from plant material or animal waste. Biomass is converted into energy by burning wood, manufacturing ethanol-based fuel from plants, capturing methane gas from decomposing organic material, and a variety of other means.

direct solar heat gain: The process by which the Sun's thermal radiation enters a building through windows; impinges on floors, walls, and furniture; and is reradiated back into the interior space as heat.

net-zero-energy home: A residential building that requires no net input of energy over the course of a year.

passive solar design: A holistic building design approach in which the location, orientation, architectural configuration, and interior features of a building are chosen with a focus on maximizing solar heat gain in the winter and minimizing it in the summer.

solar heat gain coefficient: A metric used in the window rating system of the National Fenestration Rating Council. This coefficient measures the fraction of solar radiation that is admitted through a window.

stack ventilation: In architectural design, the practice of using upper-level openings to exhaust naturally rising hot air.

READINGS

Johnston and Gibson, *Green from the Ground Up*.

———, *Toward a Zero Energy Home*.

QUESTIONS

- 1 To what extent is the physical orientation of your home consistent with passive solar design principles?
- 2 To what extent are your home's window sizes and locations consistent with passive solar design principles?

The Plain Old Telephone Service

This lecture begins a four-lecture introduction to telecommunications technology, by focusing on the traditional landline telephone. The plain old telephone system is a technology that changed the world and still holds considerable merit from an engineering perspective. This system has many technological limitations, but the enduring advantage of the traditional analog system over its recent digital competitors is unprecedented reliability. In most places today, when you pick up your landline phone, you'll get a dial tone 99.999% of the time. And unlike your cell phone or computer, the plain old telephone service will still work when the lights go out.

Telecommunications

- ▶ In general, any modern telecommunications system works by encoding information in a **carrier** signal and then sending it from one location to another through a communications **channel**. The carrier can be an electrical current, a light beam, or an electromagnetic wave. The encoding can be **analog**, meaning that the signal is continuously varying, or **digital**, meaning that it's made up of a series of on-off pulses, representing ones and zeroes.
- ▶ The channel is the pathway through which the stream of information is sent. If the pathway is a physical medium—such as a copper wire, **coaxial cable**, or fiber-optic **line**—then we call it a circuit, though it's

telecommunications systems

Encoding

- analog
- digital

Carrier

- light
- electrical current
- electromagnetic wave

Channel

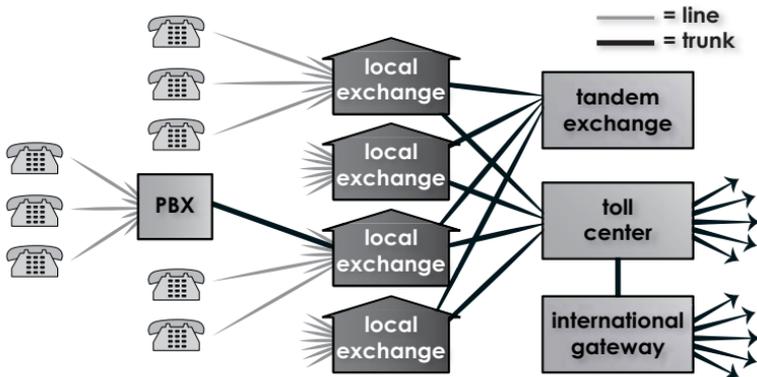
- wire (circuit)
- wireless (logical path)

important to recognize that one circuit can carry multiple channels. If the medium of transmission is wireless—as would be the case with radio, microwave, or infrared communications—then the channel is defined as a logical path, rather than a physical one.

The Landline Telephone System

- ▶ The low-tech end of the telecommunications spectrum is your local landline telephone system, which uses analog encoding of an electrical carrier signal that's transmitted on a single-channel circuit of copper wire. Today, in a telecommunications environment dominated by technologies far more sophisticated than this one, the landline phone system is known as the **plain old telephone service (POTS)**.
- ▶ Plain old telephone service is, indeed, old. The telephone was patented by Alexander Graham Bell in 1876, and by the late 19th century, a reasonably well-developed telephone network was operating in the United States.
- ▶ Apart from rotary dialing, which was introduced in the 1930s, and touch-tone dialing, introduced in 1963, the local end of this system has changed remarkably little since then. Conversely, virtually every aspect of our telecommunications system above the local level has changed radically in just the past 20 years.
- ▶ The **public switched telephone network (PSTN)** is the telecommunications system within which the plain old telephone service resides. At the lowest level of this network are individual subscribers and groups of subscribers, the latter corresponding to residences in an apartment building or offices in a commercial establishment.
- ▶ These groups are connected to a **private branch exchange (PBX)**, a switching system that allows both internal communication between any two subscribers within the group and external communication between any subscriber and the outside world. For both individual subscribers and PBXs, the gateway to the outside world is a higher-level switching

public switched telephone network



system called the **local exchange**, housed within a facility called the central office.

- ▶ Each individual subscriber is directly connected to the local exchange by a **subscriber line**—also called a **local loop**—while the PBX is connected by a local exchange **trunk**. In telecommunications lingo, “lines” and “trunks” are basically the same thing—except that a line is designed to support the calling load associated with one person, while a trunk is designed to support multiple users.
- ▶ In the past, the local exchange consisted of a platoon of human telephone operators, who established phone connections between subscribers by physically plugging pairs of wires into a switchboard. Today, the exchange still performs this switching function, but the process is now fully automated.



telephone operators

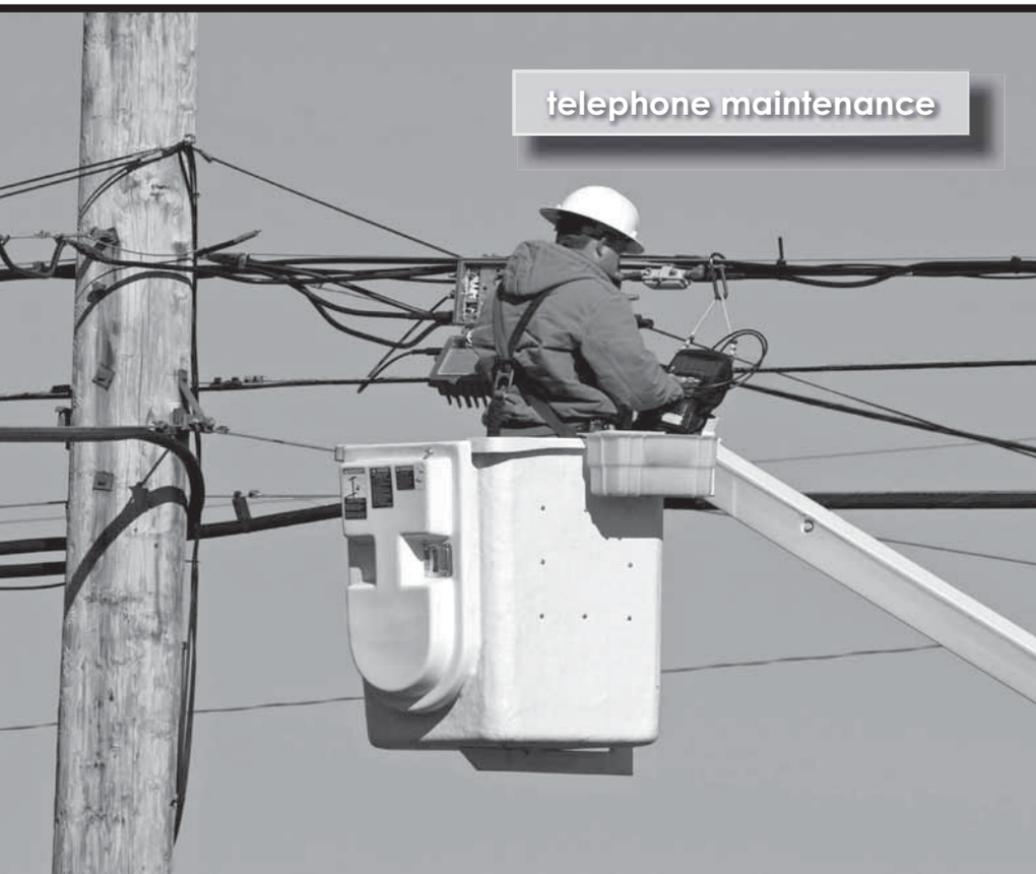
- ▶ In the United States, every local exchange is assigned a three-digit code, which corresponds to the 4th, 5th, and 6th digits of your 10-digit telephone number. Each one is unique within its assigned area code, which is why we need area codes. Every individual line that connects to a local exchange—either directly or through a PBX—is assigned its own four-digit code, called the subscriber number, and these are the final four digits in your phone number.
- ▶ If you're placing a call to another subscriber within the same exchange, the call is simply routed through the local exchange to the recipient. If you're calling a subscriber who's located in the same city but connected to a different exchange, the call is passed up to the next level in the network hierarchy, a facility called a **tandem exchange**, sometimes called a tandem switch, and then routed back down through the relevant local exchange to the intended recipient. If you're calling someone in a different area code, the transmission will be routed through a **toll center** and onward, and if the recipient is in another country, it will also pass through an **international gateway**.

- ▶ The two components of the public switched telephone network with which we interact directly every day are the telephone and the subscriber line. The subscriber line is a simple pair of thin copper wires running from your telephone directly to the local exchange. Often called the local loop, these two wires constitute a direct current electrical circuit that closes when you lift the telephone handset from its cradle and opens when you set it back down.
- ▶ This circuit is powered by a large bank of batteries located at the local exchange; that's why, when your electrical power fails, your landline phone keeps working.
- ▶ The signal passing through the local loop receives no electrical amplification, and because the strength of any electrical signal loses power, or attenuates, significantly as it's transmitted through a copper wire, the local loop is typically less than 2 miles long.
- ▶ One of the marvels of the plain old telephone system is that these two little copper wires carry so many different kinds of information—the dial tone, ringtone, busy signal, dialed numbers, and incoming and outgoing voice signals. In recent years, we've also added call-waiting, caller ID, speed dialing, conference calling, Internet communications through digital subscriber line (DSL) service, and maybe even data from your home security system or thermostat.
- ▶ All of these information streams are controlled and synchronized by your local exchange, which keeps everything moving in the right direction. Impressively, a single local exchange serves as the terminus for thousands of subscriber lines and must often manage many thousands of transactions simultaneously.
- ▶ A standard landline phone has the following main components.
 - On the handset, it has a **microphone**, which converts sound waves into variations in an electric current, and a **speaker**, which converts these variations in electric current back into sound.

- Within the housing, there is a switch, which closes the local loop circuit when you lift the phone handset “off the hook”; a ringer, which remains permanently connected to the central switching office, even when the handset is “on the hook”; and some electronic circuitry.

Operating the Plain Old Telephone Service

- ▶ The largest cost associated with operating the plain old telephone service is in stringing, connecting, and maintaining all of the copper wires. Phone companies have used two interesting technologies to keep this cost manageable.



telephone maintenance

- ▶ The first is the multi-pair cable, a single cable that bundles together as many as 8400 separate insulated copper wires to create 4200 local loops. Within the cable, pairs of wires are twisted together at different pitches (meaning that they're wound together with different numbers of twists per foot) to minimize electromagnetic interference between wires. Without this feature, your conversation would bleed over into other subscribers' phone lines.
- ▶ The two wires constituting your home's local loop are connected into the nearest multi-pair cable at a splice case. But, to make this connection, the telephone lineman must be able to distinguish your specific pair of wires from the other 4199 pairs in the cable. This is possible because of an ingenious color-coding system that uses only 10 colors.
- ▶ The efficiency of multi-pair cable notwithstanding, it's still inherently inefficient to run a separate local loop from each individual subscriber all the way to the local exchange. This is particularly true because a given line is typically in use for only a small portion of each day. To address this issue, many local phone systems now use a device called a **remote concentrator**. The principal function of this device is **multiplexing**, the process of combining many signals into a reduced number of transmission circuits.
- ▶ Until relatively recently, concentrators merely reduced the number of **twisted pairs** en route from subscribers to the local exchange. But today, the digital communications revolution has created more sophisticated forms of multiplexing that are also far more efficient.
- ▶ Now, the remote concentrator in your neighborhood probably converts the analog representation of your voice into digital form and then interweaves it with hundreds or even thousands of other conversations and sends it along to the local exchange on a single wire or optical fiber.
- ▶ For several decades, the higher levels of the public switched telephone network have been gradually changing from analog to digital, and today, the system is almost entirely digital beyond the local exchange. Many people have now forgone landline phones entirely, in favor of their cell

phones or voice over Internet protocol (VoIP). And many new homes are being connected to their exchanges with optical fiber rather than copper wire, in anticipation of the day—sometime soon—when the entire system will be digital from end to end.

TERMS

analog: In telecommunications, a continuously varying signal that is analogous to the sound waves it represents.

carrier: In telecommunications, an electromagnetic signal in which information is encoded for transmission.

channel: In telecommunications, the pathway through which a stream of information is transmitted.

coaxial cable: A high-capacity telecommunications cable developed as a replacement for twisted copper wires in the interexchange trunks of the public switched telephone network (PSTN).

digital: In telecommunications, a signal that is made up of a series of on-off pulses, representing ones and zeroes.

international gateway: In the public switched telephone network (PSTN), a switch through which international calls are routed.

line: In the public switched telephone network (PSTN), a telecommunications link designed to support the calling load associated with one person.

local exchange: In the public switched telephone network (PSTN), a switch through which all subscribers and private branch exchanges (PBX) communicate with each other and with other exchanges. The local exchange is typically housed in a building called the central office.

local loop: In telecommunications, a pair of copper wires running from the subscriber's telephone to the local exchange. Also called a **subscriber line**.

microphone: A device that converts sound waves into an electrical signal.

multiplexing: In telecommunications, a process by which multiple signals or data streams are combined into one signal for transmission over a shared medium.

plain old telephone service (POTS): The traditional landline telephone system.

private branch exchange (PBX): In telecommunications, a switch that allows both internal communication between any two connected subscribers and external communication through the local exchange.

public switched telephone network (PSTN): A worldwide telecommunications system consisting of conventional telephone lines, fiber-optic cables, microwave links, communications satellites, and undersea cables that are interconnected at exchanges using standardized communications protocols.

remote concentrator: In the public switched telephone network (PSTN), a low-level switch in which multiple subscriber lines are multiplexed into a single trunk for transmission to the local exchange. At a remote concentrator, the signal is usually converted from analog to digital as well.

speaker: A device that converts an electrical signal into sound waves.

subscriber line: In telecommunications, a pair of copper wires running from the subscriber's telephone to the local exchange. Also called the **local loop**.

tandem exchange: In the public switched telephone network (PSTN), a switch located immediately above the local exchange in the network hierarchy.

toll center: In the public switched telephone network (PSTN), a switch through which long-distance calls are routed.

trunk: In the public switched telephone network (PSTN), a telecommunications link designed to support the calling load associated with multiple users.

twisted pair: Two twisted copper wires that are used for subscriber lines in the public switched telephone network (PSTN).

READINGS

Goleniewski, *Telecommunications Essentials*, chapters 1–4.

Hayes, *Infrastructure*, chapter 7.

QUESTIONS

- 1 How can a telephone landline carry two phone conversations on a single two-wire circuit?
- 2 In a world of ever-expanding mobile communications, is the traditional landline telephone worth preserving as an element of our telecommunications infrastructure?

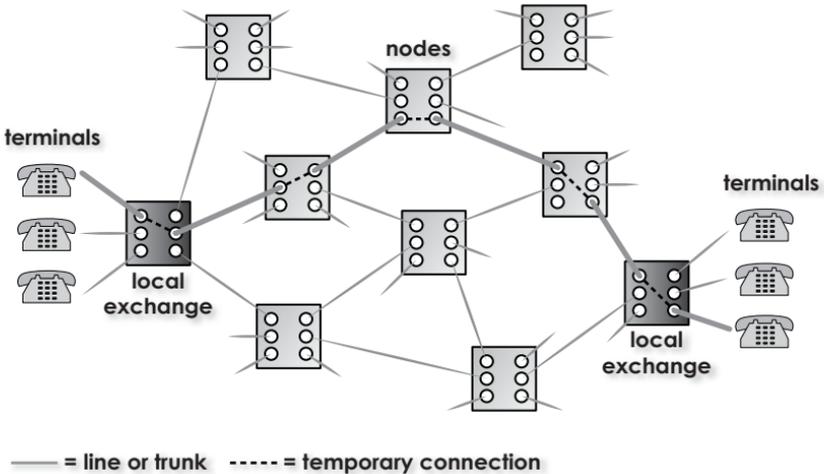
The Global Telecommunications Network

The public switched telephone network (PSTN) is a vast array of conventional phone lines, fiber-optic cables, microwave links, communications satellites, and undersea cables that are interconnected at exchanges using standardized communications protocols and are fully integrated with cellular networks and the Internet. Thanks to this vast network—and the international standards that ensure consistent transmission of information across it—your phone can connect to any other telephone in the world in a matter of seconds. In this lecture, you will learn how the PSTN operates as a communications network.

Telecommunications Networks

- ▶ There are two basic types of telecommunications networks: **circuit-switched networks** and **packet-switched networks**. In a circuit-switched network, information is transmitted through a dedicated communications channel from one terminal through one or more intermediate nodes to another end station. The connection must be fully established, end to end, before the transmission can begin, and then it's released after the transmission is complete.
- ▶ Circuit-switched communications are characterized as continuous, exclusive, and temporary: continuous, because once the connection is established, it's maintained for the duration of the call; exclusive, because the channel isn't shared with any other users during the transmission; and temporary, because the connection only exists for the duration of the call.
- ▶ The quintessential example of a circuit-switched network is the public switched telephone network (PSTN). In the PSTN, the terminals are usually telephones. And the nodes are switches, located at the local, tandem, and toll exchanges. The switch was once a human, plugging

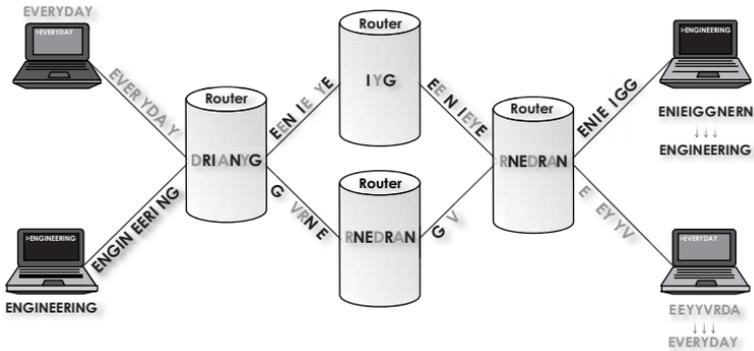
circuit-switched network



wires into a switchboard manually, but today, the term “switch” refers to a specialized computer that’s used to establish connections between transmission lines.

- ▶ A fundamental characteristic of the PSTN is that the switches are smart, so your telephone doesn’t have to be. When you dial a phone number, it’s the switches that figure out the optimum path through the network to your recipient, taking into account the current level of traffic and working around any trunks or switches that are currently out of service. It’s the switches that generate dial tones, ringtones, call-waiting, and busy signals. And it’s the switches that establish, and later release, your connection.
- ▶ The principal advantage of the PSTN’s circuit-switched architecture is quality of service. Once the connection is established, there’s minimal **latency** (delay), so the system is optimal for real-time voice traffic. The disadvantage is relative inefficiency, resulting from that fact that most

packet-switched network



phone conversations consist of approximately 50% silence. As such, that dedicated communication channel is usually operating far below its capacity.

- ▶ This limitation is ingeniously addressed in the packet-switched network, a fundamentally different network architecture that's the basis for the Internet. In a packet-switched network, a transmission (which might be voice or data) is broken up into many small chunks, called packets, which are then transmitted independently across a shared network, with each packet potentially following a different route.
- ▶ At the network nodes are devices called **routers**, which receive packets and forward them onward through the network. Each packet incorporates a header containing two key pieces of information: the address of the packet's destination and a sequence number, which is ultimately used to reassemble the packets in the correct order at their destination.
- ▶ At each node, the router processes packets independently, on a first-in–first-out basis—determining only the next node in each packet's journey. This determination is based on a routing protocol that, typically, attempts to minimize the number of nodes along the remainder of the path. All

transmission lines in a packet-switched network are shared, so packets originating from many different sources are constantly arriving in the queues of the routers. During periods of heavy traffic, these queues can cause considerable latency, and if any queue exceeds the storage capacity of its associated router, the overflow packets are simply lost.

- ▶ The major advantage of packet switching is its highly efficient use of network resources. In comparison with the circuit-switched model, packet switching also represents a decentralization of intelligence from the core of the network to its periphery. Internet routers don't need to be as smart as PSTN switches, because processors at the source and destination do most of the heavy lifting, creating and addressing packets and then reassembling them after transmission.
- ▶ This characteristic—decentralized intelligence—enhances the system's redundancy and resilience while also enabling the Internet's most characteristic feature: its capacity to grow and change in creative new ways, seemingly on a daily basis, without any centralized control.
- ▶ The disadvantages of packet switching—latency and data loss—reflect the fact that the Internet was originally designed for the efficient transmission of so-called **bursty data**—that is, data sent in short spurts, separated by long periods of inactivity.
- ▶ Today, however, we're demanding much more from the Internet—streaming video, voice over Internet protocol (VoIP) telephone service, interactive online gaming—communications that are anything but bursty. And the Internet is changing to accommodate these new demands.

The Public Switched Telephone Network

- ▶ The PSTN was designed and optimized for transmission of the human voice. Voice transmissions can take either of two forms: analog or digital. In the modern PSTN, most voice signals start out as analog in the local loop, are converted to digital for transmission through the core, and then are converted back to analog for the “last mile” to the recipient.

- ▶ For analog transmission, when pressure waves propagating from your vocal chords encounter the microphone in your landline telephone, these continuous variations in volume are converted into similar variations in both electrical current and voltage, which then propagate through the subscriber line to your local exchange. Digital transmission is a bit more complicated, because it requires that we represent this irregular, continuous waveform as a series of ones and zeroes.
- ▶ The transmission medium that was once used throughout the PSTN is a pair of twisted copper wires. Today, most of the copper in the core of the network has been replaced by transmission media with far greater capacity, but the twisted pair is still used extensively in the local loop of the plain old telephone service. Copper wires are both less expensive and easier to work with than all of the alternatives.
- ▶ The **bandwidth** and speed of copper cables pale in comparison with other transmission media. And beyond their limited capacity, copper wires suffer from severe signal attenuation, which causes the signal to get weaker over a very short distance, and high susceptibility to **noise** and interference, which introduce errors into the data stream.
- ▶ In the local loop of the PSTN, these limitations are addressed simply by locating local exchanges or concentrators within 2 miles of the subscribers they serve. But in a long-distance trunk, the only way to compensate for signal attenuation is to place **amplifiers** at approximately one-mile intervals along its length. An amplifier uses externally supplied energy to boost the power of an input signal and then sends the amplified output signal down the line.
- ▶ Because amplifiers work in only one direction, the core of the PSTN was developed with four-wire circuits, rather than the two-wire configuration of your local loop. When two people have a conversation over a four-wire circuit, half of the conversation travels in one pair of wires and the other half goes the other direction in the other pair.
- ▶ However, in modern interexchange voice transmissions, you'll never have one set of wires all to yourself. Various types of multiplexing are

used to squeeze many simultaneous calls into one circuit. The original type, called **frequency-division multiplexing**, was the principal form of multiplexing used in the PSTN until the system's digital transition in the mid-20th century.

- ▶ For telephone, only 24 conversations (at most) can be multiplexed onto a standard four-wire copper circuit. Beyond that, the higher frequencies required for multiplexing cause excessive power loss. This limitation was overcome with the development of coaxial cable.
- ▶ Although coaxial cable, or coax, can support a bandwidth of 370 times more than a twisted pair, the use of coax is severely constrained by the need for amplifiers spaced at roughly 1.5-mile intervals along transmission lines. This limitation led to a new technology—**microwave communications**—deployed into the core of the PSTN as a replacement for coax on long-distance trunks.

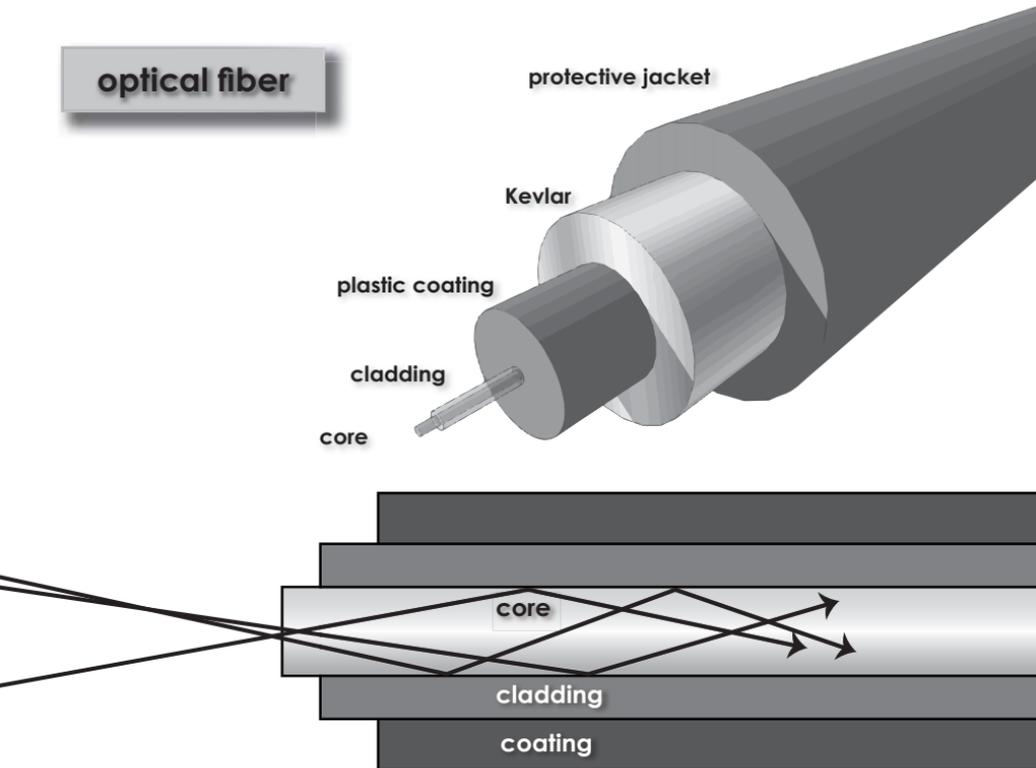


- ▶ Microwave is a form of electromagnetic radiation, a very high-frequency radio wave, which can be focused into a narrow beam and used for point-to-point communication. Microwaves provided a substantial improvement over coax in terms of both capacity and flexibility of deployment.
- ▶ Today, microwave trunks in the PSTN have mostly been replaced by fiber-optic cable, but microwave remains valuable for situations where stringing cable can be problematic—for crossing deserts or mountainous regions and for connecting to remote locations. The microwave band is also used for satellite communications. And this technology is finding all kinds of new applications in private, commercial point-to-point communications over relatively short distances.

From Analog to Digital

- ▶ In the latter half of the 20th century, the PSTN was gradually converted from entirely analog to mostly digital. There were two principal drivers for this transition: Analog signals are far more susceptible to loss of fidelity than digital signals, and digital communications are well suited to a fundamentally different and more powerful type of multiplexing, called **time-division multiplexing**.
- ▶ In the modern world of telecommunications, nothing is more remarkable than optical fiber. First deployed in 1979, **fiber-optic communication** involves the transmission of a digitally encoded light beam through a tiny fiber of glass. The digital encoding is accomplished by a computer-controlled laser, which sends pulses of light through an optical fiber to represent ones and zeroes.
- ▶ The performance of optical fiber as a transmission medium is simply mind-boggling. Not only is its rate of attenuation so low that repeaters are typically needed only every 500 miles, and not only is optical fiber immune to electromagnetic interference, but each of the tiny strands of glass can comfortably carry the equivalent of more than 600,000

optical fiber



simultaneous digitally multiplexed phone conversations. With new, advanced multiplexing methods currently being fielded, that number grows to about 3 million. Optical fiber has sparked a communications revolution, while fundamentally changing the PSTN.

TERMS

amplifier: In telecommunications, a device that uses externally supplied energy to boost the power of an input signal.

bandwidth: A range of frequencies.

bursty data: Data transmitted through a network in short spurts, separated by longer periods of inactivity.

circuit-switched network: A communications network in which information is transmitted through a dedicated communications channel from one terminal through one or more intermediate nodes to another terminal. The connection must be fully established, end to end, before the transmission can begin, and then it is released after the transmission is complete.

fiber-optic communication: Transmission of information by directing a digitally encoded light beam through a tiny fiber of glass.

frequency-division multiplexing: A form of multiplexing in which the total bandwidth available for transmission is subdivided into a series of nonoverlapping frequency subbands, each of which constitutes a separate communications channel.

latency: Delay in a telecommunications transmission.

microwave communication: Use of very high-frequency electromagnetic radiation for point-to-point communication.

noise: In telecommunications, the progressive corruption of a signal as it moves along a transmission path.

packet-switched network: A network in which a transmission is broken up into many small chunks (called packets), which are then transmitted independently across a shared network, with each packet potentially following a different route.

router: A device that manages the flow of information through a node in a packet-switched network.

time-division multiplexing: A form of multiplexing in which multiple signals are transmitted over a common path by assigning a unique sequential time slot to each signal.

READINGS

Goleniewski, *Telecommunications Essentials*, chapters 4, 5, 8, and 11.

Hayes, *Infrastructure*, chapter 7.

QUESTIONS

- 1 What can we learn about the nature of technological development from the evolution of communications media, from twisted copper wire to coaxial cable to microwave to optical fiber?
- 2 Explain the concept of multiplexing.

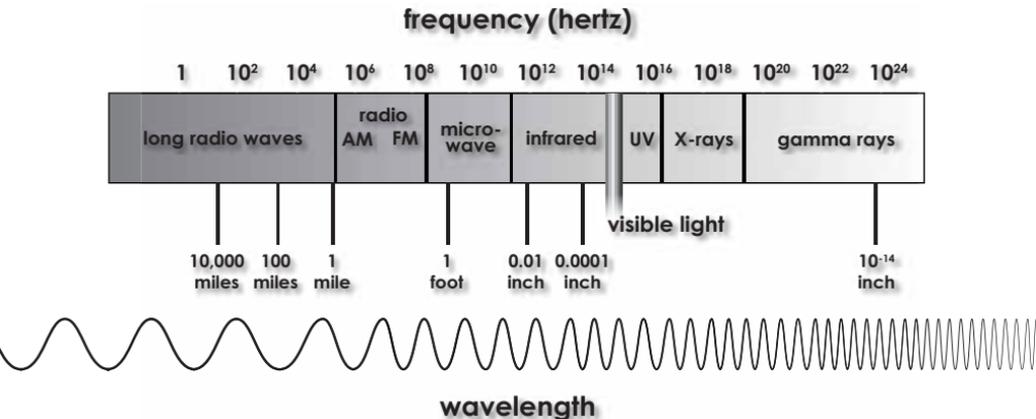
Cellular Phone Technology

The cellular telephone is a major part of the ongoing telecommunications revolution. The ubiquity of this device has changed our lives in profound ways—and, for this reason alone, we should know something about the underlying technology. But cellular technology is also worth knowing about because it's often more problematic than the other technologies in our lives. Why do you sometimes lose your connection for no apparent reason? Why does your battery consumption vary so wildly? In this lecture, you will discover that being an informed user of cellular technology can be beneficial to your everyday life.

Cellular Communication

- ▶ At the most fundamental level, **cellular communication** involves analog or digital encoding of a radio carrier signal. Thus, we can't understand the technology without first understanding radio.
- ▶ Anytime electrons move at varying speed, they generate electromagnetic radiation that propagates through space at the speed of light. Because electromagnetic radiation oscillates as it propagates through space, it's characterized as a wave phenomenon, and like any wave phenomenon, it can be classified according to its frequency.
- ▶ At the bottom end of the **electromagnetic spectrum** is low-frequency, long-wave radio. The progressively higher frequencies are conventional radio, including the frequency bands used for AM and FM radio, microwave, infrared, visible light, ultraviolet light, X-rays, and gamma rays.

the electromagnetic spectrum



- ▶ Low-frequency radio waves are called long waves because the physical length of a wave is inversely proportional to its frequency. In general, electromagnetic waves with low frequency can travel much farther than those on the opposite end of the spectrum, but they have significantly lower capacity for carrying information.
- ▶ Electromagnetic waves with high frequency have far greater capacity, by virtue of their greater bandwidth, but they also attenuate more quickly, and their waveforms are so small that they're highly susceptible to atmospheric interference.
- ▶ For these reasons, most wireless communications use the middle of the electromagnetic spectrum. Mobile phones generally operate primarily in the frequency band just above FM radio, from about 700 to 2500 megahertz.

- ▶ With radio communication, a transmitter generates an alternating current that's been modulated, or electronically mixed, with a signal representing the information that's being transmitted. This alternating current is passed through an electrical conductor called an **antenna**. Because the current is oscillating, it generates electromagnetic waves at the same frequency as the current, and these waves radiate off the antenna into space at the speed of light. As long as the frequency of the alternating current is in the radio frequency range, the resulting electromagnetic waves will be radio waves.

- ▶ At the other end of the transmission, the process happens in reverse. The electromagnetic waves impinge on the receiving antenna, inducing a corresponding electrical current. This signal can then be demodulated to retrieve the transmitted information.

- ▶ The cell phone is really just a radio transmitter-receiver. In this sense, the cell phone isn't new technology; it's not fundamentally different from walkie-talkies, with two exceptions.
 - A walkie-talkie typically operates on only one radio frequency, so you can either transmit or receive at any given time, but not both. Most cell phones operate on two frequencies to facilitate simultaneous transmission and reception, called **full-duplex communication**.

 - The original walkie-talkies were all analog devices, and while the first generation of cell phones was analog as well, all modern mobile devices encode and transmit information digitally.

- ▶ Although the cell phone is conceptually similar to a simple walkie-talkie, what makes a cellular network so complex is the need to handle millions of conversations simultaneously. The electromagnetic spectrum is a finite resource; if we start handing out two frequencies per mobile phone, we'll run out of frequencies long before we run out of mobile phone users.

cell tower

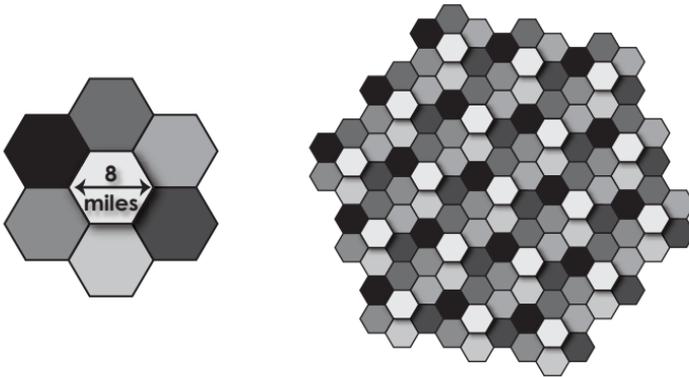


- ▶ Cellular networks handle this challenge through a concept called **space-division multiplexing**. A geographic region is subdivided into a regular grid of smaller areas called cells. Each cell has its own antenna and **base station**. These cells are normally hexagonal to provide efficient coverage with minimal overlap.
- ▶ Within each cell is a base station, which incorporates the radio transmitters, receivers, and antennas that communicate with all mobile devices located within the cell. The power of the radio transmitter is deliberately limited so that frequencies can be reused in other cells without causing interference between transmissions. A factor called the **cellular reuse pattern** determines which other cells to reuse.

Commercial Cellular Technology

- ▶ The first generation of commercial cellular technology was launched in Japan in 1979 and called “1G,” for “1st generation.” In this system, each cell was about 8 miles wide, and the cellular reuse pattern was 7—meaning that each cell of this 7-cell module used a completely different set of frequencies. When we replicate this reuse pattern across the countryside, we see that it always provides a buffer of two cells between any pair of cells using the same frequencies.
- ▶ The electromagnetic spectrum is a highly constrained resource, so it’s tightly controlled by government regulatory agencies, such as the U.S. Federal Communications Commission. In 1G networks, the FCC typically allocated enough radio spectrum to provide each service provider with 832 voice channels, resulting in each of the 8-mile-diameter cells being able to serve 60 simultaneous conversations.
- ▶ The history of cellular technology development since then has revolved around the need to handle an ever-increasing number of users, demanding evermore bandwidth for both voice and data communications and evermore reliable and responsive service.

first-generation (1G) commercial cellular technology



- ▶ One response to these challenges has been simply to use more efficient cellular reuse patterns. Another response has been to use smaller cells in areas where larger numbers of users are congregated. The capability to subdivide big cells into little ones was an important new feature of the second-generation cellular network standard, 2G, which was first deployed in 1991 in Finland.
- ▶ Since then, we've seen the establishment of microcells (each about a mile wide), picocells (typically 500 feet or less), and even femtocells (about 30 feet). Picocells and femtocells are often used to extend cell coverage indoors—the former for office buildings, shopping malls, train stations, and similar large public facilities and the latter for small businesses and individual homes.
- ▶ Beyond the improved coverage, smaller cells also have the advantage of requiring less power, both at the base station and in your phone. Today, most cell phones have variable power output, and the cellular base station actually controls your phone's power level to maintain an adequate signal, while minimizing drain on your battery.

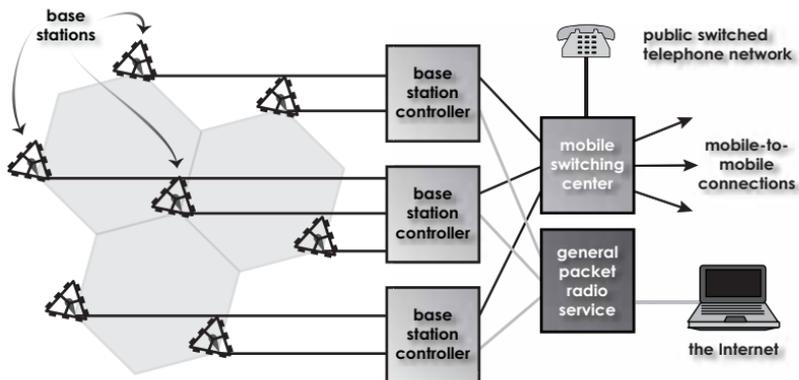
- ▶ But this relentless subdivision of cells has some significant downsides, too. One is the added cost of more antennas, more base stations, and more network interconnections. But a more significant drawback of smaller cells is a larger number of **handoffs**, which occur every time a user moves from one cell to another. The handoff is a complex process requiring considerable computation and information exchange between your phone and the cellular network. Demanding too many handoffs in too short a period of time can cause problems.
- ▶ Often, this challenge is addressed by using macrocells—sometimes as large as 20 miles across—in rural areas and along highways, where users are most likely to be crossing from cell to cell at higher speed, and by using smaller cells in areas where people are likely to remain in one cell for relatively longer periods of time, such as shopping malls and office buildings.
- ▶ Allowing the use of variable cell sizes contributed significantly to enhanced capacity in second-generation cellular networks. But the more important contributor, by far, was the change from analog encoding in 1G to digital encoding in 2G. This change allowed for the encryption of voice transmissions, addressing a particularly serious security concern with wireless communications.
- ▶ And it opened the door to the transmission of data as well as voice. Text messaging was an integral part of the 2G standard, and it paved the way for the smartphones of today. But most importantly, the switch from analog to digital allowed for significantly more efficient use of the limited electromagnetic spectrum assigned to cellular communications, because it incorporated multiplexing—or, to be more precise, it incorporated a more sophisticated form of multiple access.
- ▶ In 1G networks, the simple system of allocating two frequencies to each user is called **frequency-division multiple access**. The major technological advance in 2G networks was a new system called **time-division multiple access**, which combines the concepts of frequency-division and time-division multiplexing. By itself, time-division multiple

access provides an eightfold increase in capacity over the simpler frequency-division system used in 1G networks.

- ▶ But with increased capacity comes a significant new technological challenge: synchronizing transmissions by mobile devices located at different distances from the cellular antenna. This challenge has been addressed in third-generation, or 3G, wireless networks, which were first deployed in 2001.
- ▶ The efficiencies gained from this system arrived just in time to accommodate the explosion in demand for mobile connectivity that accompanied the introduction of the smartphone in 2007. But demand has only increased since then. Enhanced 3G and recently introduced 4G systems have addressed this by incorporating advanced antennas; data compression; duplexing techniques, which allow a single channel to share both the outgoing and incoming halves of a conversation; and new schemes for multiple access.
- ▶ All of these changes require an extraordinary level of coordination between the research and development community, government regulators, standards organizations (both domestic and international), wireless carriers, and hardware and software developers. And this challenge can only ever be met temporarily, because demand is ever increasing, and new technological paradigms are constantly emerging. In fact, the 5G standard is due out in 2020.

Communication between Phone and Network

- ▶ The radio communication link between your mobile device and the nearest cellular base station is only the tip of the iceberg. The base stations are just intermediate nodes in a far more extensive network of networks. Tens, or even hundreds, of base stations are connected to devices called **base station controllers**, which, in turn, are tied together by regional facilities called **mobile switching centers**.



- ▶ The mobile switching center operates like a local exchange in the public switched telephone network, and it also provides the interface between the cellular network and the PSTN. The mobile switching center sets up and releases end-to-end calls—both mobile-to-mobile and mobile-to-PSTN calls.
- ▶ Base station controllers are also connected to the **general packet radio service**, a packet-switched network that's overlaid on the circuit-switched phone network and handles all Internet data packets passing between your mobile device and the Internet.
- ▶ Another important function that's performed jointly by the base station controllers and mobile switching centers is the handoff of calls from cell to cell. Calls do occasionally get dropped during handoffs.

TERMS

antenna: An electrical conductor that generates electromagnetic waves for wireless transmission of information or that receives such transmissions.

base station: In a cellular network, a facility that contains the transmitters, receivers, and antennas required for communication with mobile devices located within the associated cell.

base station controller: A device that connects multiple cellular base stations to their associated mobile switching centers.

cellular communication: A wireless communication system that uses analog or digital encoding of a radio carrier signal.

cellular reuse pattern: In a cellular communication system, the number of adjacent cells in a module that cannot use the same frequencies.

electromagnetic spectrum: The range of frequencies associated with electromagnetic radiation.

frequency-division multiple access: A system for wireless communication in which multiple conversations are transmitted independently between various mobile devices and a cellular base station on different frequencies.

full-duplex communication: A form of communication that allows for simultaneous transmission and reception.

general packet radio service: A packet-switched network that is overlaid on the circuit-switched phone network and handles all Internet data passing between mobile devices and the Internet.

handoff: In a cellular network, the transfer of control of a mobile device from one cell to another.

mobile switching center: In a cellular network, a facility that connects to and controls all cellular base stations within a region. The mobile switching center sets up and releases end-to-end calls—both mobile-to-mobile and mobile-to-PSTN calls.

space-division multiplexing: A form of multiplexing in which a geographic region is subdivided into a regular grid of smaller areas called cells, each with its own antenna and base station.

time-division multiple access: A system for wireless communication in which the available frequency spectrum is first subdivided into channels, and then, within each channel, multiple communication devices are each assigned a specific time slot for transmission.

READINGS

Goleniewski, *Telecommunications Essentials*, chapters 13 and 14.

Hayes, *Infrastructure*, chapter 7.

QUESTIONS

- 1 What is the fundamental technological challenge that has driven the development of successive generations of cellular technology since 1979?
- 2 What are some possible causes of a lost cellular connection?

Satellites orbit hundreds or even thousands of miles above the Earth's surface, yet they directly influence our daily lives—for example, when we check tomorrow's weather forecast or use a GPS device for navigation. In this lecture, you will learn about the two types of satellites that have the greatest direct impact on our everyday lives: communications satellites, which facilitate global telecommunications in a wide variety of forms, and navigation satellites, which are used to determine locations on the Earth's surface or in the air by transmitting radio signals to mobile receivers.

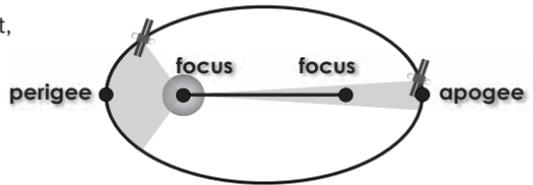
Orbital Mechanics

▶ Modern orbital mechanics has its roots in Kepler's laws of planetary motion, first published by Johannes Kepler in 1609, and in the more general laws of universal gravitation and celestial motion, published by Sir Isaac Newton in 1687.

▶ The following are five key concepts in orbital mechanics.

- A satellite's orbit is elliptical, with the planet located at one **focus** of the ellipse.

- On an elliptical orbit, the closest point to the planet is called the **perigee**, and the farthest point is called the **apogee**.



- A line drawn from the planet to the satellite sweeps out an equal area in an equal period of time at any location in the orbit. Thus, the satellite moves faster when it's closer to the planet and slower when it's farther away.

- Once a satellite is in orbit, the orbit's characteristic shape and **orbital period** won't change, unless the satellite is subjected to an applied force, such as thrust from a rocket engine or drag caused by interaction with the atmosphere.
- As the two foci of an elliptical orbit get closer together, the shape of the orbit becomes progressively closer to a circle. Thus, a circular orbit is really just a special case of an elliptical orbit—one for which the two foci correspond.
- ▶ For a circular orbit, the **altitude** of the satellite—that is, its distance from the Earth's surface—never changes. Thus, its speed is constant. And, according to Kepler's laws, both the speed and orbital period for a body orbiting the Earth can be calculated. The speed and period of a circular orbit depend only on its radius, not on the mass of the satellite.
- ▶ Earth orbits are generally classified in four categories.
 - A **low earth orbit** (LEO) is a circular orbit with an altitude between 100 and 1240 miles above the Earth's surface.
 - The medium earth orbit is a circular orbit with an altitude between 1240 and 22,236 miles.
 - At the precise altitude of 22,236 miles is the **geostationary orbit (GEO)**.
 - The elliptical orbit is used to transfer a satellite from one circular orbit to another and for other special purposes.
- ▶ The orbital period of a geostationary orbit is calculated as 23.93 hours, which is exactly equal to one **sidereal day**. A sidereal day is the time it takes for the Earth to complete one full rotation with respect to a nonrotating frame of reference.
- ▶ Because a GEO satellite's orbital period exactly matches the Earth's rotational period, the satellite remains perfectly stationary at one point in the sky, from the perspective of an observer on the Earth's surface.

That's why we can aim our satellite dishes at one point in the sky and never have to adjust them, and that's why most communications satellites use geostationary orbits.

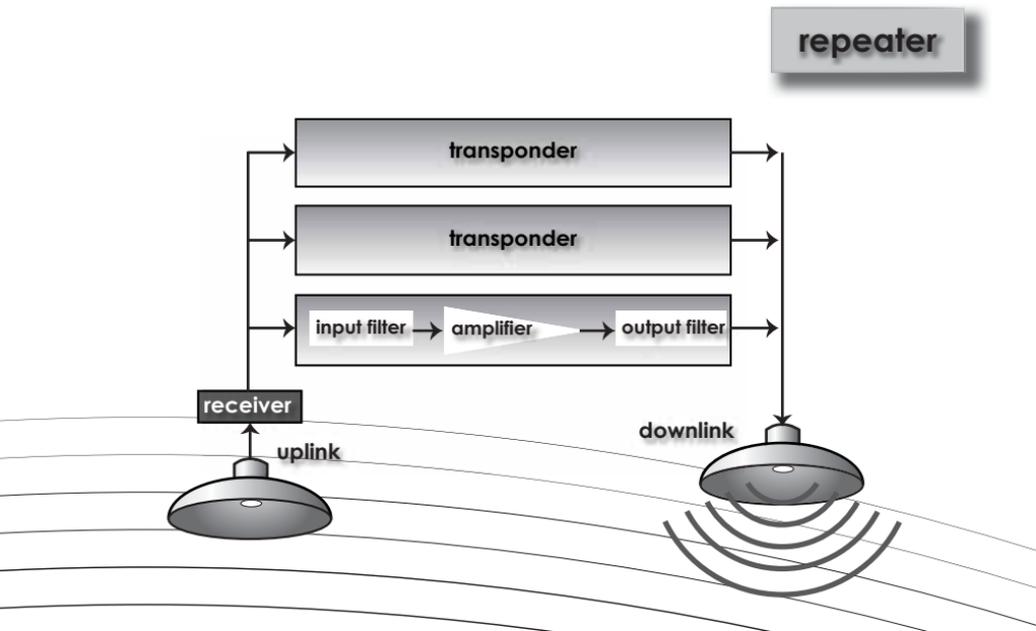
- ▶ There is only one geostationary orbit, located 22,236 miles above the equator, and there are currently about 400 satellites in it. If these satellites were uniformly spaced around the circumference of the orbit, the distance between them would be more than adequate—more than 400 miles.
- ▶ However, they're not uniformly spaced, because a communications satellite needs to be more-or-less centered over its coverage area to do its job. Thus, GEO satellites are concentrated most densely over the most technologically developed regions of the world. In these regions, it's not unusual for GEO satellites to be separated by fewer than 5 miles. Given that they're moving at almost 7000 miles per hour, this isn't a lot of space.
- ▶ To minimize the possibility of collisions and electronic interference, each satellite is assigned an **orbital station** (which is really just a longitude) by the International Telecommunication Union. A station in a geostationary orbit is one of the world's most prized pieces of real estate.

GEO Satellites

- ▶ Commanded by a ground-based control center, a satellite in space orients itself, deploys its antennas and solar arrays, senses the positions of the Earth and Sun, establishes communication links, and becomes operational.
- ▶ The satellite is composed of two major components: the **mission payload** and the support platform (also called the bus). The bus is responsible for transporting the mission payload in orbit; it provides electrical power, **attitude** (orientation in space) control, temperature control, and orbital adjustments.

- ▶ The typical communications satellite has two large solar arrays, which serve as its sole source of electrical power in orbit. They're also used to charge batteries, which supply power when the satellite passes through the Earth's shadow. The arrays must rotate continuously on a specific axis, following the Sun as the satellite orbits the Earth. As the satellite orbits, its communications antennas must remain pointed at their designated coverage areas on the Earth's surface, called the **footprint**.
- ▶ To control the satellite's position and attitude, the bus uses two separate systems: rocket thrusters and **reaction wheels**. The array of rockets typically includes one primary orbit maneuver thruster and 12 attitude and orbit control thrusters, arranged such that the bus can be propelled or rotated in any direction with great precision.
- ▶ These thrusters are used for the final insertion into geostationary orbit, for the initial orientation of the satellite, and for station keeping—the process of adjusting the orbit to keep the satellite at its prescribed altitude and longitude. The bus controls the satellite's attitude with reaction wheels.
- ▶ The bus also includes a telemetry system that continuously transmits information about the satellite's status—attitude, power production, propellant supply, temperature, and so on—to a command and control station on the ground.
- ▶ The mission payload is the satellite's communications package. The basic function of a communications satellite is to receive radio signals (called **uplinks**) from a ground-based transmitter, amplify these signals, shift their frequency, and then retransmit them as **downlinks** to the Earth's surface.
- ▶ Communication services handled by satellites include television, radio, Internet, telephone, and some specialized business communications. Satellite telephone service is generally much more expensive than the use of landlines, cell phones, and undersea cables (particularly with the advent of fiber optics), so satellite phones are used primarily in remote areas that don't have other phone services available.

- ▶ Because the geostationary orbit is so high, there's a substantial delay in radio transmissions to and from the satellite—about a quarter of a second each way—even though these transmissions travel at the speed of light. This delay can cause problems for two-way communications and certain types of data transmission, such as Internet gaming, but it poses no problems for one-way broadcasts, such as radio and television—hence, the growing popularity of these services.
- ▶ The mission payload consists of two main elements: antennas and a repeater. Most communications satellites are equipped with at least two dish antennas. These may be used for communication on two different frequency bands, or they may be aimed at two different footprints on the ground, but each antenna is generally used for both receiving and transmitting. Because radio signals are so weak by the time they reach the altitude of a geosynchronous orbit, these antennas must be as large as possible.
- ▶ The **repeater** includes a radio receiver, which receives the uplink and feeds it to an array of parallel **transponders**, each corresponding to a particular service—television, voice, Internet, radio—and a particular frequency band.



- ▶ Most repeaters have 24 or more transponders. Each contains an input filter, which separates out the particular signal that's assigned to that service; an amplifier, which boosts the strength of the uplink signal by as much as 10 million times; and an output filter, which performs the frequency shift required to prevent the uplink and downlink from interfering with each other.
- ▶ This system communicates with a worldwide network of ground-based telecommunications ports (or **teleports**), which exist to provide customers with access to satellites. Equipped with antennas, transmitters, receivers, and routing equipment, the teleport receives signals from a variety of sources—such as the public switched telephone network, the Internet, and cable television networks—and sends these signals as uplinks to the appropriate satellites. Similarly, the teleport receives satellite downlinks that originated elsewhere and routes them to the appropriate destination.
- ▶ Not all downlinks pass through the teleport. Over the past few decades, development of high-frequency, high-powered satellite transmission capability has stimulated the development of the direct broadcast satellite service, which produces broadcast signals capable of being received by the small dish antennas that have become so popular with consumers. This capability, more than any other, is driving the continued economic viability of satellite communications.

LEO Satellites

- ▶ Geostationary satellites aren't the only type of communications satellite. A relatively recent alternative is to use a constellation of LEO satellites, which are less expensive to launch, require less power for signal transmission, and are much less susceptible to the transmission delays associated with GEO satellites.
- ▶ However, these systems require far more satellites to provide adequate coverage of the Earth's surface. And because LEO satellites move at

such high speeds, transmissions are constantly being handed off from one satellite to the next.

- ▶ In recent years, one of the greatest impacts of satellite technology on our everyday lives has been the advent of highly accurate satellite-based navigation through the **global positioning system (GPS)**, which uses a constellation of 32 satellites in medium earth orbit, flying at an altitude of 12,600 miles, with a corresponding orbital period of 12 hours. These satellites move in multiple orbital planes, such that any point on the ground theoretically has a line of sight to at least six satellites at any time.
- ▶ Each GPS satellite continuously transmits messages indicating the exact time of transmission and exact position of the satellite at the time of transmission. The GPS receiver in your car detects this signal and, using its own internal clock, calculates the time that was required for the signal to travel from the satellite to the receiver.
- ▶ Because electromagnetic waves propagate at the speed of light, this time measurement must be extremely precise. However, no matter how precise it might be, this measurement can never be perfectly accurate, because the clock in your GPS receiver can never be perfectly synchronized with the clock in the satellite.

TERMS

altitude: In orbital mechanics, the distance from the surface of a planet to an orbit. The radius of an orbit is equal to the altitude plus the radius of the planet.

attitude: The orientation of a satellite, spacecraft, or other orbiting body in three-dimensional space.

apogee: The highest point in an elliptical orbit.

downlink: A radio signal transmitted by a satellite to Earth.

focus: One of two points on which the geometric construction of an ellipse are based.

footprint: A satellite antenna's designated coverage area on the Earth's surface.

geostationary orbit (GEO): A circular orbit with an altitude of 22,236 miles above the Earth's surface. A satellite in a GEO orbits the Earth in exactly one sidereal day.

global positioning system (GPS): A satellite-based system for navigation on the surface of the Earth.

low earth orbit (LEO): A circular orbit with an altitude between 100 and 1240 miles above the Earth's surface.

mission payload: The communications package in a communications satellite.

orbital period: The time required for one orbit.

orbital station: The longitude to which a satellite in a geostationary orbit is assigned.

perigee: The lowest point in an elliptical orbit.

reaction wheel: An electric-powered wheel that is used for attitude control in a satellite.

repeater: In satellite communications, a device that receives an uplink, boosts the strength of the signal, shifts its frequency, and retransmits it back to Earth as a downlink. A repeater incorporates a receiver and multiple transponders.

sidereal day: The time required for the Earth to complete one full rotation with respect to a nonrotating frame of reference. A sidereal day is 23.93 hours long.

teleport: A ground-based communications port that provides customers with access to satellite communications.

transponder: In satellite communications, a device that filters out a particular signal from an uplink, amplifies that signal, shifts its frequency, and then retransmits it as a downlink. Multiple transponders are incorporated within the repeater of a satellite.

uplink: A radio signal transmitted to a satellite.

READING

Welti, *Satellite Basics for Everyone*.

QUESTIONS

- 1 What are the key advantages and disadvantages of using the geostationary orbit for communications satellites?
- 2 What is the importance of the elliptical orbit in placing communications satellites into geostationary orbit around the Earth?

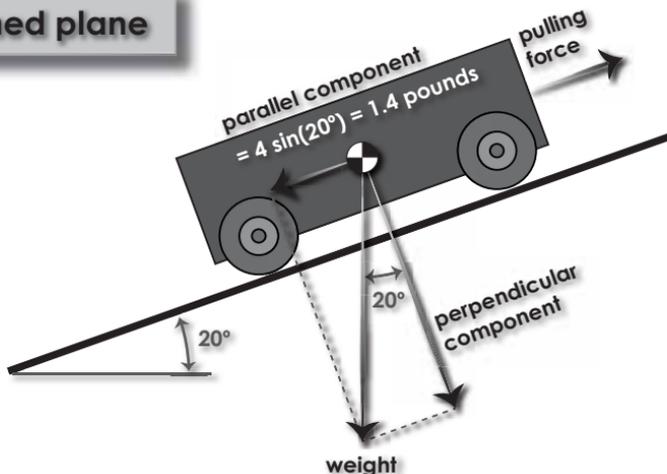
Simple Machines around the House

In this lecture, you will learn about the classical simple machines—a concept that originated with the ancient Greeks and is still useful for classifying and understanding mechanical devices today. Although the official number of simple machines has varied through the ages, most modern lists include the following six: the inclined plane, screw, wedge, lever, wheel and axle, and pulley. All of these devices have the same fundamental purpose: to change the magnitude or direction of a force.

The Inclined Plane

- ▶ The **inclined plane**, or ramp, allows us to lift an object using less force than that object's weight. In the science of mechanics, forces are represented as vectors. A **vector** is a mathematical quantity that has both magnitude and direction. For the purpose of analysis, it's often useful to resolve a vector into its perpendicular components. These

inclined plane



two components—horizontal and vertical—are equivalent to the original force. We can calculate the magnitudes of these two components using trigonometry, or we can estimate the magnitudes quite accurately from a scale diagram.

- ▶ This magnification of effort is called **mechanical advantage**. But mechanical advantage always comes at a cost. With an inclined plane, to lift something with less force, you have to pull it through a greater distance. All of the simple machines achieve mechanical advantage by trading force for distance, in much the same way.

The Screw

- ▶ The **screw** is used as a fastener in innumerable products and devices, but it's also found in other interesting places, such as a corkscrew, an automobile jack, and even the rotating blades of a modern snowblower. In all cases, the purpose of the screw is to convert rotational motion into linear motion, or to convert a rotational force (which is called a **moment**) into a linear force, directed along the length of the screw.
- ▶ A moment is the tendency of a force to cause rotation. Its magnitude is the force times the distance from the force to the center of rotation.
- ▶ How does a screw change a moment into a linear force? First, it always requires two matched sets of threads: one moving and one stationary. With a nut and bolt, both sets of threads are manufactured. With a lag bolt, the bolt cuts the second set of threads into the wood as you drive it in. In either case, the bolt's angled threads translate the applied moment into a larger longitudinal force. This force drives the lag bolt into the wood and clamps the nut and the bolt head tightly against the connected material.
- ▶ In this sense, a screw works much like an inclined plane that's been formed into a cylindrical shape. In fact, wrapping an inclined plane around a shaft creates a screw.

- ▶ Visualizing the threads of a screw as an inclined plane also helps us determine the mechanical advantage of the screw. If we visualize the screw as being rotated by a tangential force, moving around the circumference of the shaft, then the distance through which the force moves corresponds to the horizontal edge of the inclined plane. And the distance through which the screw moves corresponds to the vertical edge. Because mechanical advantage is always about trading force for distance, the theoretical magnification of force by the screw is equal to the ratio of those two lengths.
- ▶ The magnification of force is “theoretical,” because the usable mechanical advantage of a screw is always substantially reduced by **friction**. All machines—simple and otherwise—are susceptible to this problem, but the screw’s performance is more dramatically affected by friction than most machines, because the longitudinal force on the shaft clamps the surfaces of the moving and stationary threads so tightly together. A metal screw typically loses more than 80% of its theoretical mechanical advantage to friction.
- ▶ Yet this isn’t necessarily a bad thing. Thanks to friction, screws and bolts are said to be self-locking. Not all simple machines are self-locking. For example, levers often are not.

The Wedge

- ▶ The third of our simple machines is the **wedge**. A simple example is a timber wedge, which is used for splitting wood. To understand how a wedge works, we’ll examine it with the device embedded in a log and subject to the downward force of a hammer.
- ▶ Let’s isolate the wedge and identify all of the forces acting on it. The hammer is applying a large downward force, which augments the weight of the wedge. An important principle of mechanics tells us that this can’t possibly be the only force acting on the wedge. The

principle of equilibrium is based on **Newton's first law** of motion, which says that an object at rest will remain at rest unless it's acted on by an unbalanced force.

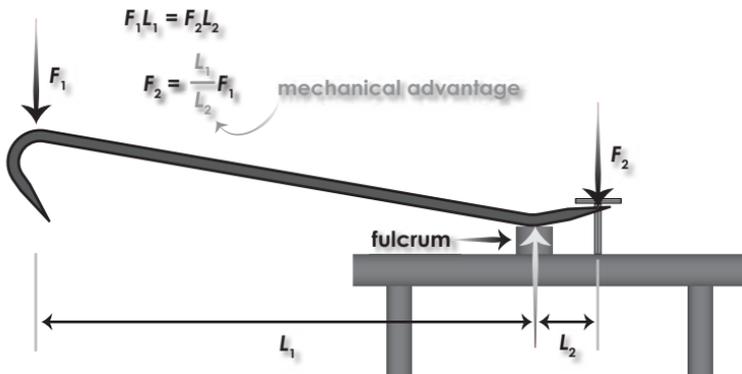
- ▶ When the wedge isn't moving, we can conclude that all of the forces acting on it must be in balance. Therefore, there must be other forces acting on the wedge to counterbalance the downward force. And the only places where these forces can possibly occur are at the contact surfaces between the wedge and the wood.
- ▶ Anytime two objects are in contact with each other, forces are developed at the point of contact. They're called **normal forces**, because they always act perpendicular (or normal) to the contact surfaces. Normal forces always occur in pairs—equal in magnitude but opposite in direction—applied to the two objects. Thus, the normal forces associated with the wedge are directed upward and inward on the wedge and directed outward and downward on the wood.
- ▶ This phenomenon is a manifestation of **Newton's third law**: For every action, there's an equal and opposite reaction.
- ▶ The two large normal forces generated by the wedge push the material apart and eventually cause it to split.

The Lever

- ▶ Once again, let's isolate the **lever** and identify all of the forces acting on it. Your hand applies a force on one end of the lever. On the opposite end, the bar is pulling upward on the nail; thus, according to Newton's third law, the nail must be pulling downward on the bar. The principle of equilibrium says that all forces on the bar add to zero, so there must be a large upward force at the **fulcrum**, counterbalancing the two downward forces at the ends.

lever

equilibrium:

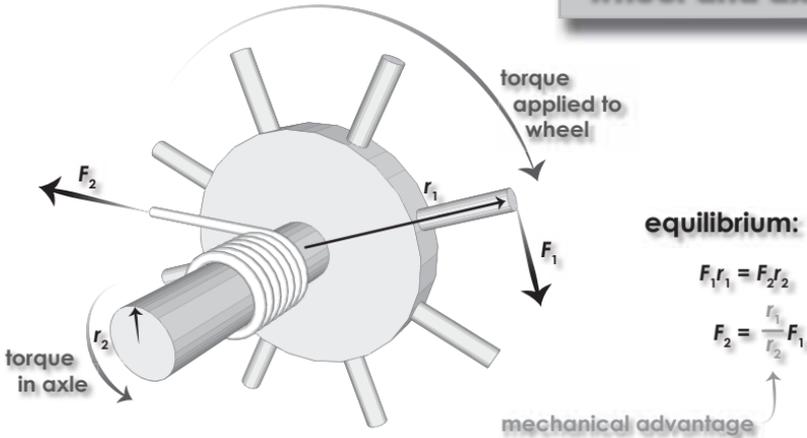


- ▶ The principle of equilibrium also tells us that all moments acting on a stationary object must add to zero. The clockwise moment caused by your hand must be equal to the counterclockwise moment caused by the load. The lever magnifies your effort; that's the mechanical advantage.
- ▶ But here, once again, is the inherent trade-off common to all simple machines: In order to gain that mechanical advantage in force, you need to move your hand a greater distance.
- ▶ Levers are everywhere. A fishing pole is a lever for extracting a fish from water. Scissors and pliers each consist of two levers connected together at a common fulcrum. Different types of simple machines are often combined into a single device for enhanced effectiveness.

The Wheel and Axle

- ▶ Once you understand the lever, you effectively understand the **wheel and axle**, too. In the context of simple machines, the term “wheel and axle” usually doesn't refer to a rolling wheel but, rather, to a wheel with a fixed axle. The classic example is a device called a windlass, which

wheel and axle



operates by converting a force applied to the wheel into a much larger force in the rope wrapped around the axle. The analogous modern household device is the reel you use to wind up your garden hose, but many other common devices work on the same principle. These include the steering wheel in your car, the knobs on appliances and faucets, and even the screwdriver. The wheel and axle is really nothing more than a rotating lever.

- In this system, the torque applied to the wheel is equal to the torque developed in the axle. But because the torque is equal to the force times the radius, the force at the axle must be larger than the force applied to the wheel—by a factor of the ratio of the wheel radius to the axle radius, which is the mechanical advantage.

The Pulley

- The **pulley** is a device that, in its simplest form, only changes the direction of a force without magnifying it. A single pulley allows you to lift a certain amount of weight upward by pulling downward with the same amount of weight. There's no mechanical advantage.

pulley



- ▶ But for a typical household example, such as the lifting apparatus on blinds, we're more concerned with convenience than with the capacity to lift a heavy weight. In this application, lifting a heavy weight is the goal, but incorporating mechanical advantage would defeat the purpose of the machine.
- ▶ It is possible to rig a single pulley so that it does provide mechanical advantage. In the rigged arrangement, the pulley moves with the load rather than being fixed, and the weight is supported by two legs of the lifting rope rather than just one. Therefore, the mechanical advantage is 2 to 1; we can lift 2 pounds with a 1-pound pull. However, as always, there's a trade-off: In order to lift the weight a given distance, we need to pull twice the length of rope through the pulley.

TERMS

friction: A resisting force developed at the interface between two bodies. The friction force is oriented parallel to the contact surface in the direction that opposes motion.

fulcrum: The pivot on which a lever rotates.

inclined plane: A simple machine that allows one to lift an object using less force than the weight of the object.

lever: A simple machine that converts an applied force to a larger force through rotation about a fulcrum.

mechanical advantage: Magnification of effort by a mechanical device.

moment: The tendency of a force to cause rotation, expressed in units of force times distance.

Newton's first law: An object at rest (or in motion at constant velocity) will remain at rest (or in motion at constant velocity) unless it is acted on by an unbalanced force.

Newton's third law: For every action, there is an equal and opposite reaction.

normal force: A force developed at the interface between two bodies. The normal force is always oriented perpendicular to the contact surface.

pulley: A simple machine that changes the direction of a rope or cable.

screw: A simple machine that converts rotational motion into linear motion or converts a moment into a linear force directed along the length of the screw.

wedge: A simple machine that converts a longitudinal force to two large lateral forces.

wheel and axle: A simple machine that converts an applied force to a larger force through rotation.

READING

Riley, Sturges, and Morris, *Statics and Mechanics of Materials*.

QUESTIONS

- 1 Identify the simple machines incorporated into the following common tools: hammer, shovel, chisel, screwdriver, wire cutter, can opener, clamp.
- 2 Identify the simple machines incorporated into the following parts of an automobile: steering wheel, windshield wiper, radio knob, hand brake.

User-Centered Design

In this lecture, you will explore the design of everyday things—a subject that draws on the broader fields of human factors engineering, ergonomics, and engineering psychology. This lecture will extensively draw on the work of Dr. Don Norman, an engineer and cognitive psychologist who pioneered the field of user-centered design and has written several well-regarded books on the subject. The focus will be on faucets because they provide particularly clear illustrations of basic design principles in a context that's familiar to all of us.

The Water Faucet

- ▶ The water faucet is a very common everyday technology that allows us to experience good and bad design many times a day. When we use a faucet, we expect it to perform two specific functions: controlling the water temperature and controlling the rate of flow.
- ▶ A very common faucet design features two knobs: one for hot water and one for cold water. When we operate this device, it usually responds as we expect, as long as it's been installed consistent with the unofficial worldwide convention of placing the hot-water control on the left and the cold-water control on the right. Unfortunately, this convention is sometimes ignored, and when that happens, we often operate the knobs incorrectly, no matter how well marked they might be.
- ▶ Another common convention is that rotating a knob to control flow should be analogous to turning a bolt. Clockwise rotation tightens a bolt and thus should reduce flow; counterclockwise rotation loosens a bolt and thus should increase flow. The valves in your plumbing system operate this way, and the convention makes sense, because many such devices actually do use a screw to open and close an internal stopper.

- ▶ The problem is that some manufacturers disagree with this convention. They propose an alternate paradigm: that controls intended for two hands should reflect the symmetry of the human body and thus should operate as mirror images. When this mirror-image paradigm is applied to a faucet with two knobs, three distinct problems arise.
 - We're so conditioned to the traditional convention that when we encounter this alternative convention, we'll invariably turn one knob or the other in the wrong direction on the first attempt.
 - Even if we're expecting the mirror-image paradigm, there's no clear convention for which direction is on and which is off, so we'll still get it wrong on the first attempt about half the time.
 - A design that's optimized for two hands breaks down entirely when we operate it with one hand.
- ▶ Applying the mirror-image paradigm to faucet knobs is unequivocally bad design, particularly because the inherent flaws in this paradigm can be corrected so easily. Some faucets are able to use the mirror-image paradigm but with a clear mode of operation, thanks to the simple substitution of handles for knobs.

mirror-image faucet



- ▶ When the faucet is shut off, the handles are both pointed outward—a clear signal that the mirror-image paradigm is being used. It’s also clear that both handles must be rotated forward to turn the water on, because there isn’t enough clearance behind them to allow rearward rotation. Furthermore, the shape of the handles sends a subtle message that they are to be grasped and pulled, further reinforcing our intuition about how they should work.
- ▶ Another advantage of handles is that with the water running, the position of the handles provides a visual indicator of the state of the system. A faucet handle is so effective at communicating how it’s supposed to be operated that it even works when it’s misused.
- ▶ These examples illustrate three important points about design for usability.
 - The differences between poor design and good design can be quite subtle, but the effects are often dramatic.
 - Solely by virtue of their shape, size, and placement, physical objects send us subtle messages about how they can be or should be used. These messages are called **affordances**, and high-quality design invariably takes advantage of affordances to improve the interactions between technological devices and people.
 - Physical limitations or **constraints** also can communicate how a device should or shouldn’t be used.
- ▶ Its effectiveness notwithstanding, mirror-image handles aren’t perfect. The two controls on the faucet don’t directly address either of the two functions we expect of a faucet: control of temperature and control of flow rate.
- ▶ To achieve either function, we usually have to operate both controls simultaneously. Controlling the temperature is particularly problematic, because the only way to test whether we’ve achieved the correct mixture of hot and cold is to place a hand into the stream of water, even

as we need both hands to make the adjustments. Moreover, once we get the temperature right, increasing or decreasing the flow rate without inadvertently changing the temperature is nearly impossible.

- ▶ Some faucets attempt to address these issues by providing a single handle to control both functions. The handle moves both side to side, for temperature control, and front to back, for flow-rate control. In the side-to-side direction, left corresponds to hot and right corresponds to cold. But the flow-rate control is more problematic, because it's not clear which direction should correspond to greater flow and which should correspond to less flow.
- ▶ With some single-handle faucets, we pull the handle toward us to turn the water on, and this makes sense, because downward movement of the handle corresponds logically to the downward flow of water. But with other models, we lift up to turn on the water—and this makes sense, too, because we tend to associate “up” with “on” and “down” with “off.” This is a **mapping** problem: The association between a control and its associated action is ambiguous.
- ▶ Effective designs address this ambiguity with affordances and constraints. On some faucets, the handle is nearly horizontal and relatively close to the spout when the water isn't running. There isn't enough room to push it downward, so it's fairly obvious that we need to lift up to turn on the water.
- ▶ A well-designed single-handle faucet is functionally superior to any faucet that uses separate controls for hot and cold water, because the configuration aligns more closely with the functions we expect from this device. The single-handle design also has a much-improved **feedback** mechanism: We can operate the control with one hand and feel the temperature of the water with the other.
- ▶ But it's still not perfect, because the merging of two functions into a single control often makes it difficult to perform one function independently of the other. And the whole system falls apart in

cases where the spout can rotate from side to side—and, thus, it no longer provides a point of reference for the middle of the handle's temperature range.

- ▶ One way to avoid problems associated with controlling two functions simultaneously is to eliminate one function entirely. There are two categories of faucets designed to do just that. The first, typically found in public restrooms, uses a fixed temperature and allows only the flow rate to be controlled. The second, common in hotel showers and recently in residential construction, uses a fixed flow rate and allows only the temperature to be controlled. Both systems are typically used to limit water consumption; they are not designed for usability.
- ▶ Hands-free faucets, soap dispensers, and paper-towel dispensers can be maddeningly user-unfriendly. The first challenge is simply recognizing that the device is, indeed, hands-free. The most common design flaw in hands-free devices is that they lack clear indicators of where the proximity sensor is and how we should interact with it.

Five Principles of Design

- ▶ Don Norman has formulated five principles of design. All five rules reflect the importance of **discoverability**: a set of characteristics that communicate what actions are possible and how they're to be performed. Designers achieve discoverability through thoughtful incorporation of affordances, **signifiers**, mapping, constraints, and feedback into their designs.
- ▶ An affordance is a message conveyed by the physical configuration or placement of an object about how people can interact with it. An affordance is both a physical property and a perception by an individual human, so discerning affordances can be somewhat subjective and culture dependent. Nonetheless, many affordances are nearly universal. Knobs afford turning and pulling, handles afford pulling, and flat plates and crash bars afford pushing.

- ▶ The word “push” on a door is a signifier, which is an explicit message about how an object is to be used. Too often we see signifiers that are needed to compensate for the designer’s failure to use affordances effectively. But signifiers are far more effective when they’re used to augment or enhance natural affordances to improve understandability.
- ▶ Mapping is the relationship between controls and the actions they control. The best mappings are natural mappings, which take advantage of physical, spatial, or logical analogies—for example, moving a control upward to raise the level of illumination or moving a control forward to initiate forward motion. Natural mappings almost always lead to understanding, while poor mappings usually lead to frustration and error.
- ▶ Constraints are physical limitations that communicate how a device can or can’t be used. The three-prong plug is a superb example. It’s physically impossible to insert it into a wall socket in any orientation other than the correct one.
- ▶ Our interactions with technology are greatly facilitated by responsive, meaningful feedback. When you press an elevator call button and it lights up, you’re satisfied that an elevator is on the way. Feedback promotes the effective use of technology; lack of feedback often discourages it.

TERMS

affordance: In user-centered design, a message conveyed by the physical configuration or placement of an object about how people can interact with it.

constraint: In user-centered design, a physical limitation that communicates how a device can or cannot be used.

discoverability: In user-centered design, a set of characteristics that communicates what actions are possible and how they’re to be performed.

Designers achieve discoverability through incorporation of affordances, signifiers, mapping, constraints, and feedback into their designs.

feedback: In user-centered design, responsive information indicating that the user's interaction with the object or device was or was not correct.

mapping: In user-centered design, the relationship between controls and the actions they control.

signifier: In user-centered design, an explicit message about how an object is to be used.

READING

Norman, *The Design of Everyday Things*.

QUESTIONS

- 1 Apply Norman's principles of discoverability—affordances, signifiers, mapping, constraints, and feedback—to evaluate the basic controls of your automobile: steering wheel, shift lever, turn signal, windshield wiper and washer switches, headlight switch, overhead light switches, heating and air-conditioning controls, door handles, and door locks.
- 2 Refrigerator-freezers typically use two separate temperature controls: one for the refrigerator and one for the freezer. However, in most cases, the system has only one thermostat, located in the freezer. The fresh-food area is cooled indirectly, by air circulated from the freezer through a controllable gate. Thus, the freezer control regulates the freezer temperature *directly*, by controlling the thermostat, and the second control regulates the temperature of the fresh-food area *indirectly*, by controlling the gate. Why is this design problematic from the perspective of user-centered design? What errors is the user likely to make because of this control system configuration?

The Internal Combustion Engine

The next four lectures will depart from your home's living space and enter your garage to explore the major technological systems that constitute your automobile. In this lecture, you will examine the technological system that has been the foundation of automotive engineering since its inception: the internal combustion engine. In the following two lectures, you will learn about the automobile's other major engineered components: the drivetrain, suspension, steering, and braking systems. These components are beautifully integrated elements of an elaborate system of systems that has been continuously updated and refined for more than a century.

The Internal Combustion Engine

- ▶ The internal combustion engine is a machine that converts the chemical energy in a hydrocarbon fuel into the mechanical energy of a rotating shaft. There are two basic types: Spark-ignition engines generally run on gasoline, while compression-ignition engines run on diesel fuel.
- ▶ At the heart of both systems is a chemical reaction involving the combustion of a hydrocarbon fuel. A hydrocarbon molecule is a chain of carbon and hydrogen atoms. Gasoline is composed of more than 100 chemical compounds. A typical example is the hydrocarbon octane, which has 8 carbon and 18 hydrogen atoms.



benzene + oxygen \rightarrow carbon dioxide + water + energy

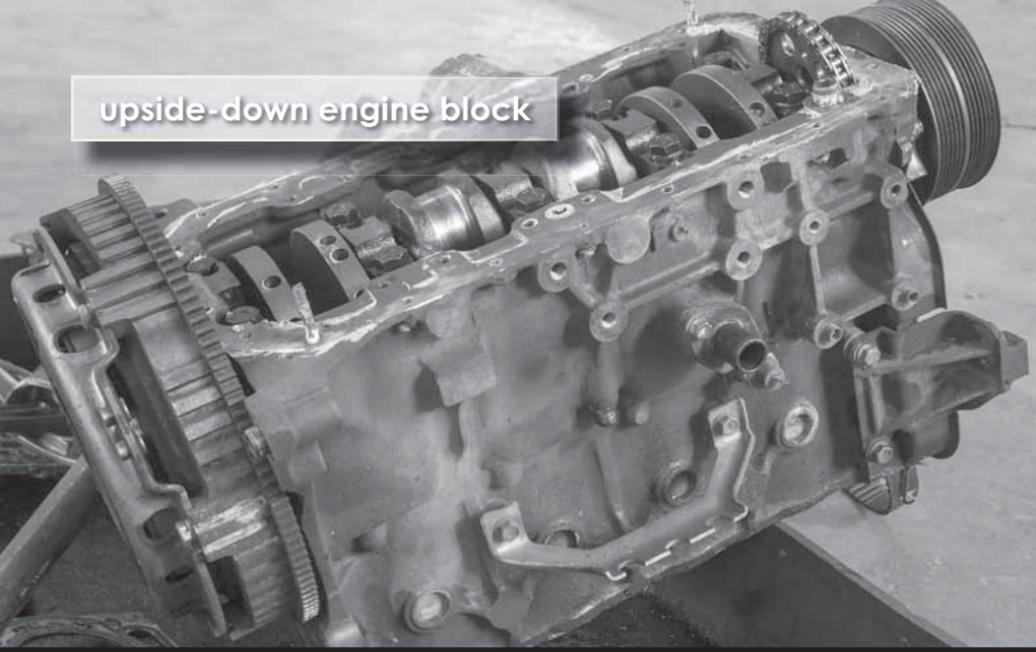
- ▶ In a spark-ignition engine, octane combines with oxygen from the air to produce carbon dioxide and water. This chemical reaction is exothermic,

meaning that it also produces energy, and it's this energy that ultimately propels your car.

- ▶ The combustion reaction takes place within cylindrical cavities that have been machined into a solid block of iron or aluminum, called the **engine block**. These cavities are called **cylinders**, which are just large enough to accommodate metal **pistons** sliding up and down within them. Near the top of each piston are several grooves, which hold metal **rings** that provide a tight seal between the piston and the cylinder walls.



- ▶ Pistons are hollow and open on the bottom to facilitate their pinned attachment to **connecting rods**, which link each cylinder to the **crankshaft**. The crankshaft is mounted within the bottom of the block, in an enclosure is called the **crankcase**. When the engine is assembled, the crankcase is closed off on the underside by the oil pan.
- ▶ The up-and-down (or reciprocating) motion of the pistons is translated by the connecting rods into rotational motion of the crankshaft, which then delivers mechanical power to the vehicle's drivetrain.
- ▶ The distance each piston moves within its cylinder is called the **stroke**, which extends between the position called the top dead center and the position called the bottom dead center. When the engine is running at normal operating speeds, the cylinders are cycling up and down many thousands of times per minute, and because the mass of each cylinder must be accelerated from a dead stop at the start of each stroke, the



upside-down engine block

engine's efficiency is enhanced by keeping the cylinders as light as possible. That's why they're hollow.

- ▶ Each cylinder is equipped with an intake valve, an exhaust valve, and a spark plug, all of which are mounted within a heavy metal lid called the **cylinder head**. The two valves are used to close off intake and exhaust ports, which are cast directly into the head.
- ▶ The cylinder, piston, connecting rod, crankshaft, valves, ports, and spark plug are the components of the engine that are directly involved in the process of producing mechanical power.
- ▶ Most automobile engines operate on a **four-stroke cycle**, meaning that each piston moves through a sequence of four different strokes, each with a specific purpose. This four-stroke sequence is then repeated over and over again, for as long as the engine is running.

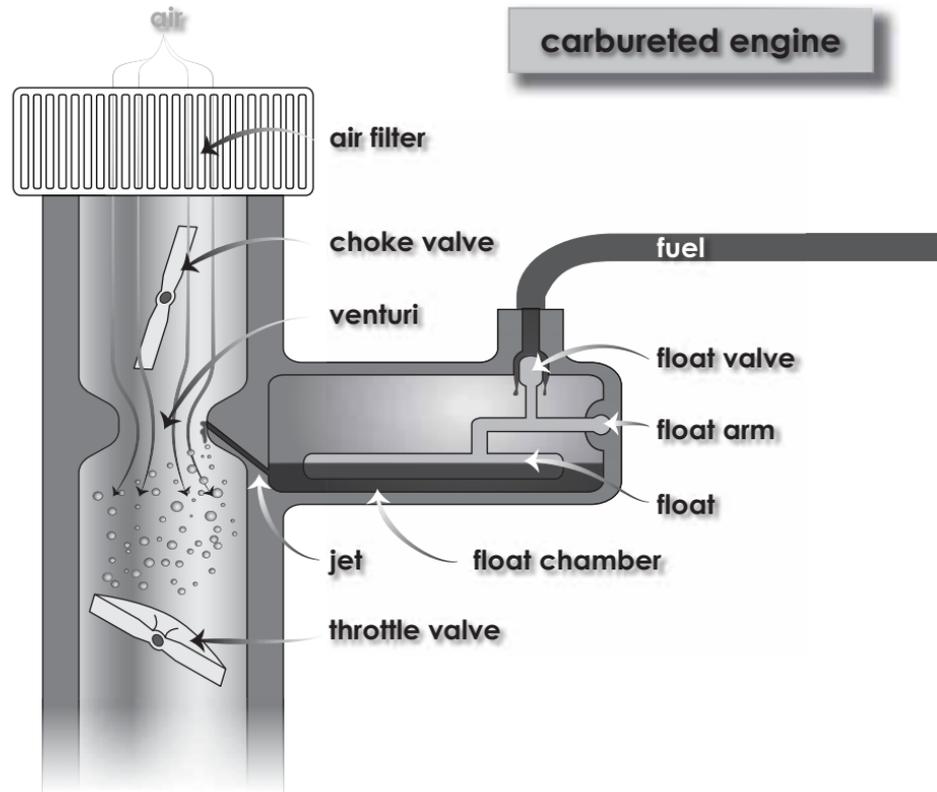
- ▶ For an engine with a simple carburetor, the first of the four strokes is the induction stroke, during which the piston moves downward in its cylinder, and the intake valve opens. A mixture of fuel and air is drawn from the carburetor through the intake port and into the cylinder, and then the valve closes.
- ▶ During the compression stroke, the cylinder moves back upward. Both valves remain closed, so the fuel-air mixture is compressed, and its temperature increases simultaneously. Just before the cylinder reaches top dead center, a pulse of high voltage is sent to the spark plug, causing an electrical arc to jump the gap between the two electrodes.
- ▶ Within the cylinder, this electric arc ignites the compressed fuel-air mixture in the cylinder, initiating the combustion reaction. The resulting heat causes a very rapid increase in pressure, which drives the cylinder back downward. This is the power stroke.
- ▶ During the exhaust stroke, the exhaust valve opens, and the piston moves back upward, expelling the cylinder's contents into the vehicle's exhaust system. These contents include the two by-products of the combustion reaction—water and carbon dioxide—plus a lot of nitrogen, a major constituent of the air originally introduced into the cylinder. The exhaust also includes small amounts of pollutants, such as unburned fuel, carbon monoxide, nitrogen oxides, and soot.
- ▶ In the four-stroke cycle, each stroke corresponds to a half rotation of the crankshaft, but power is produced during only one stroke. What keeps the piston moving up and down during the other three strokes? The answer is the other pistons. This is the principal reason why most automobile engines have four or more cylinders. The four-stroke cycles of these cylinders are staggered, such that each has its power stroke at a different time.
- ▶ The answers to the following questions are provided by the seven subsystems of an internal combustion system: valve train and the fuel, electrical, ignition, exhaust, cooling, and lubrication systems.
 - How are the valves opened and closed with such precision?

- How is the correct fuel-air mixture introduced into the cylinder during the induction stroke?
 - How does the spark plug fire at just the right moment to initiate the power stroke?
 - How are all of the combustion products removed from the automobile, and how are the fumes made safe enough to be released into the atmosphere?
 - How is the heat from thousands of explosions per minute dissipated from the engine block?
 - How is the sound from thousands of explosions per minute controlled?
 - How are all those moving parts lubricated, to keep them working freely and to prevent excessive wear?
- ▶ Every one of these subsystems must operate in perfect synchronization, or the engine won't run.

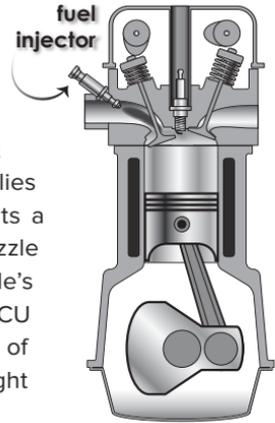
Fuel Injection

- ▶ Until the 1980s, most spark-ignition engines used a carburetor to achieve the correct fuel-air mixture to support combustion in the cylinders. In a carbureted engine, outside air is drawn through an air filter into the body of the carburetor, which has a narrow throat at its center.
- ▶ **Bernoulli's principle** tells us that when air flows through this throat, called a venturi, its speed increases and its pressure decreases. At the point of lowest pressure, a small tube is connected to a fuel reservoir, called the float chamber. Because of the low pressure in the venturi, a calibrated stream of fuel is sucked from the float chamber into the airstream.

- ▶ Below the throat is a rotating gate, called the throttle valve, which is mechanically connected to the driver's accelerator pedal. When the pedal is depressed, the throttle valve opens, and the flow of fuel and air to the engine is increased. The fuel-air mixture passes from the carburetor to an intake manifold, which divides the flow equally among all the cylinders.
- ▶ Carburetors haven't been used in automobiles since 1990, but they're worth knowing about because you're still likely to find one on your lawn mower or snowblower. But for today's automotive fuel systems, the name of the game is fuel injection, which provides more power, better fuel economy, and better emission control.



- ▶ In the most common form, called multi-port injection, fuel is supplied by devices called fuel injectors—one per cylinder—which spray fuel into each intake port, just above the valve. The car's fuel pump supplies pressurized fuel to each injector, which squirts a controlled quantity of fuel through a tiny nozzle in response to commands from the vehicle's computer, the engine control unit (ECU). The ECU monitors the throttle position and the amount of oxygen in the exhaust to determine just the right amount of fuel to deliver at any given time.



- ▶ Because multi-port injection supplies fuel upstream of the intake valve, the operation of the four-stroke cycle in a multi-port-injected engine is essentially identical to that of a carbureted engine. However, some high-performance gasoline engines, and most diesel engines, use direct injection of fuel—right into the cylinder. In these engines, the induction stroke draws in only air, and the fuel isn't injected until near the end of the compression stroke. This allows the fuel to be injected at higher pressure, resulting in a finer mist that greatly improves the combustion process.

Compression Ignition

- ▶ The compression-ignition (or diesel) engine works essentially the same way as the spark-ignition engine, except that it has no spark plugs and relies, instead, on spontaneous combustion of the fuel-air mixture at very high pressure.
- ▶ Thus, in a diesel, the induction stroke draws in only air; the compression stroke achieves significantly higher pressure and temperature than would be the case in a spark-ignition engine; fuel is injected directly into the cylinder near top dead center; and combustion occurs spontaneously, without an externally supplied spark, as soon as the fuel is injected.

- ▶ In general, diesel engines provide more power and better fuel economy than the equivalent spark-ignition engine. However, because they operate at higher pressure, they must be significantly heavier, so they're usually used for larger vehicles, such as trucks and locomotives.

TERMS

Bernoulli's principle: When the speed of a moving fluid increases, its pressure decreases, and vice versa.

connecting rod: In an automobile engine, a link that connects a piston to the crankshaft.

crankcase: In an automobile engine, an enclosure at the bottom of the engine block that houses the crankshaft.

crankshaft: In an automobile engine, a shaft that converts the reciprocating motion of a piston into rotary motion for transmission of power to the drive shaft.

cylinder: In an automobile engine, a cylindrical cavity in the engine block that contains a piston.

cylinder head: In an automobile engine, the heavy metal lid that bolts onto the top of the engine block and covers the cylinders.

engine block: In an automobile engine, the solid block of iron or aluminum that incorporates the cylinders.

four-stroke cycle: The process by which an internal combustion engine produces mechanical power through a series of four piston strokes: intake, compression, power, and exhaust.

piston: In an automobile engine, a cylindrical element is driven in reciprocating motion to produce mechanical power.

rings: In an automobile engine, metal rings mounted near the top of a piston to provide a tight seal between the piston and its associated cylinder.

stroke: In an automobile engine, the distance a piston moves within its cylinder.

READINGS

Department of the Army, *Technical Manual 9-8000*.

Gillespie, *Fundamentals of Vehicle Dynamics*.

QUESTIONS

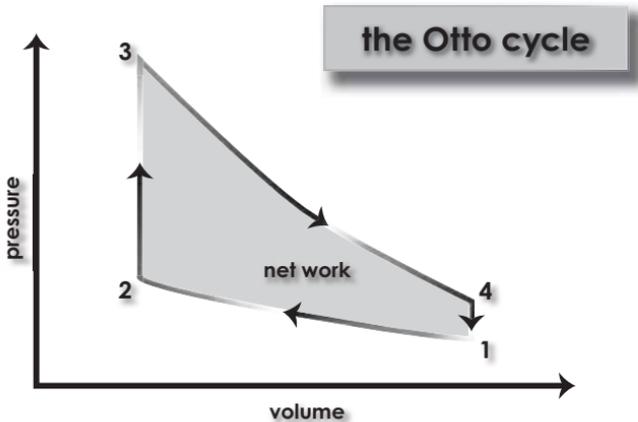
- 1** In an internal combustion engine, how is the reciprocal motion of the pistons translated into rotary motion of the drive shaft?
- 2** In the four-stroke cycle, power is produced in only one of the four piston strokes. What propels the piston through the intake, compression, and exhaust strokes?

Welcome back to the world of automotive engineering. The principal purpose for the next two lectures is to follow the transmission of mechanical power from the engine's spinning crankshaft to the vehicle's drive wheels. This function is performed by a system called the drivetrain, consisting of the flywheel, clutch, transmission, driveshaft, differential, and two drive axles. In this lecture, you will trace the transmission of engine power from the crankshaft, through the clutch and the transmission gearbox, to the driveshaft.

Torque and Power

- ▶ The four-stroke cycle of the internal combustion engine can be modeled as a thermodynamic cycle, called the **Otto cycle**, and plotted as a graph of pressure versus volume.
- ▶ Internal combustion is, by nature, not a true thermodynamic cycle—in the sense that vapor-compression refrigeration and steam power generation are true thermodynamic cycles. In both of the latter cases, there's a working fluid—either refrigerant or steam—that circulates continuously through a closed loop. In both cases, the fluid changes state (between liquid and gas), but the fluid itself doesn't change in quantity or chemical composition.
- ▶ In contrast, during the Otto cycle, the working fluid—a mixture of air and fuel—is drawn into the cylinder in discrete batches and then expelled, and its chemical composition changes over the course of each cycle, through the combustion reaction. For this reason, the Otto cycle can only approximate the behavior of an actual internal combustion engine.

- ▶ In modern automotive engineering practice, quantitative analyses of internal combustion engines are generally conducted with complex computer simulations; nonetheless, the Otto cycle still holds great value for qualitative analyses of engine performance.
- ▶ This fundamental difference between the internal combustion cycle and true thermodynamic cycles is also important because it's the basis for the name of the internal combustion engine—a system characterized by combustion occurring within the working fluid. The coal-fired steam power plant is classified as an external combustion engine, because the combustion of coal to supply heat for the boiler occurs entirely external to the working fluid.



- ▶ When the Otto cycle is plotted as a graph of pressure versus volume, the area enclosed within the cycle is mathematically equal to the cycle's net mechanical work output. We can use this relationship to determine the engine's most important performance characteristics: torque and power.
- ▶ Knowing that the area within the Otto cycle represents the work of one cylinder, we can determine the total work output of the engine by simply multiplying the area enclosed within the Otto cycle diagram by the

number of cylinders. The principle of conservation of energy tells us that the work done by the **reciprocating motion** of the pistons must be equal to the work done by the rotational motion of the crankshaft (minus any friction losses, of course). And work done by a rotating shaft is equal to its torque times the angle of rotation.

- Torque is the tendency of a force to cause rotation. When you pedal your bicycle, your foot applies a downward force to the pedal, and that force applies torque to the pedal shaft in exactly the same way that a reciprocating piston applies torque to a crankshaft.

determining torque and power from the Otto cycle

$$\text{area}_{\text{Otto}} = \text{work}_{\text{cylinder}}$$

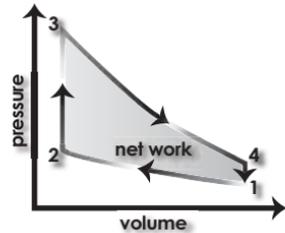
$$\text{work}_{\text{engine}} = n \times \text{work}_{\text{cylinder}}$$

(n = number of cylinders)

$$\text{work}_{\text{engine}} = \text{work}_{\text{crankshaft}}$$

$$= \text{torque} \times \text{angle of rotation}$$

$$= \text{torque} \times 4\pi$$



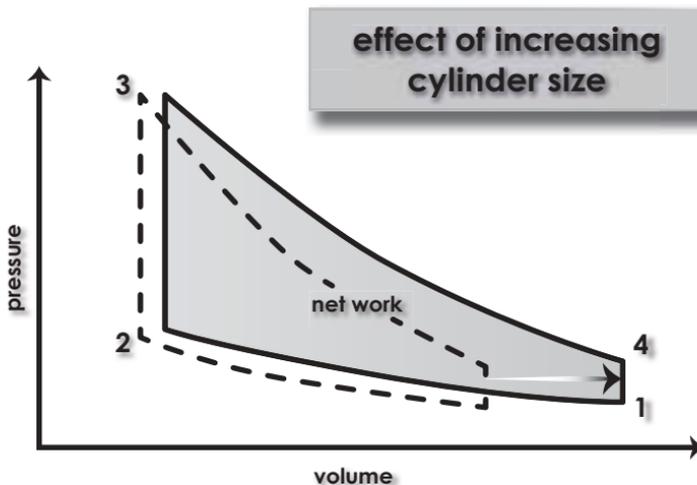
$$\text{torque} = \frac{\text{work}_{\text{engine}}}{4\pi} = \frac{n \times \text{work}_{\text{cylinder}}}{4\pi}$$

$$\text{torque} = \frac{n \times \text{area}_{\text{Otto}}}{4\pi}$$

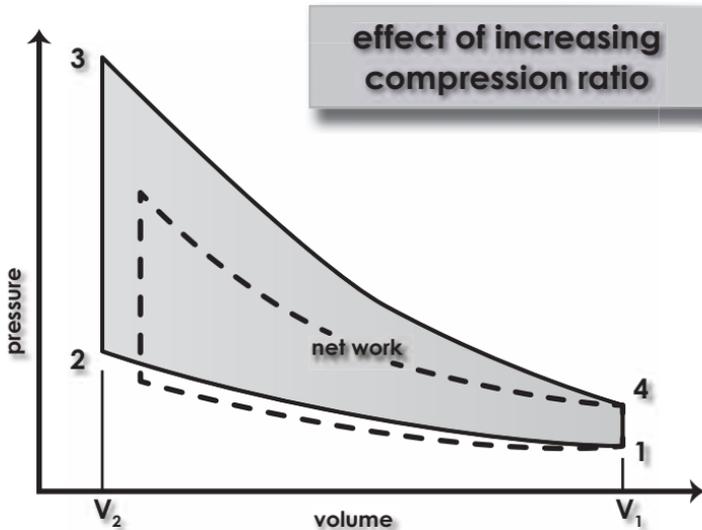
power = torque × rotational speed (radians per second or revolutions per minute/RPM)

$$\text{power} = \frac{n \times \text{area}_{\text{Otto}} \times \text{rotational speed}}{4\pi}$$

- ▶ The angle of rotation must be two full turns of the crankshaft (720°), because each four-stroke cycle rotates the shaft through two full turns. But for mathematical consistency, we must express this angle in terms of radians, not degrees. One full 360° rotation corresponds to 2π radians, so the angle of rotation for the cycle is 4π .
- ▶ With just a bit of algebra, we can express the engine's torque as a simple function of the area enclosed within the Otto cycle diagram: the number of cylinders times the area divided by 4π .
- ▶ Furthermore, the engine's net power output is simply equal to torque times rotational speed, where rotational speed is expressed in radians per second—or, with an appropriate unit conversion, as revolutions per minute (rpm). Therefore, power, too, is a function of the area enclosed within the Otto cycle diagram.
- ▶ If we multiply the **displacement** of one cylinder by the number of cylinders in the engine, we get the total displacement of the engine, a number that's common in automotive specifications. As the Otto cycle graph suggests, larger displacement corresponds to larger enclosed area, which means more torque and more power.



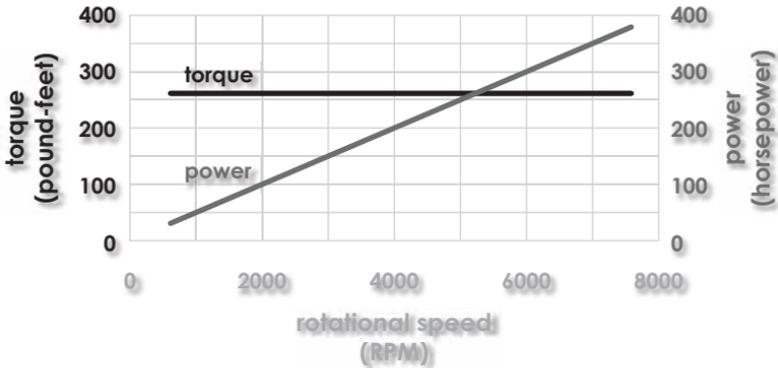
- ▶ Larger displacement can be achieved either by using more cylinders of a given size or by increasing the size of the cylinders. Increasing the cylinder size produces a theoretical increase in both torque and power that's directly proportional to the increase in the volume of the cylinder.
- ▶ Another way to increase torque and power is to increase the engine's **compression ratio**. To increase the compression ratio without changing the cylinder size, we would increase the length of the piston stroke, such that the air in the cylinder is compressed into a smaller space at top dead center. Increasing the compression ratio causes the area enclosed within the Otto cycle diagram to become both wider and taller, resulting in increased torque and power.



- ▶ Unlike the strategy of simply making the cylinders larger, increasing the compression ratio also improves the engine's efficiency, meaning that a larger proportion of the fuel's chemical energy is converted to mechanical energy. That means better gas mileage and lower emissions. But there's a limit to the effectiveness of this strategy.

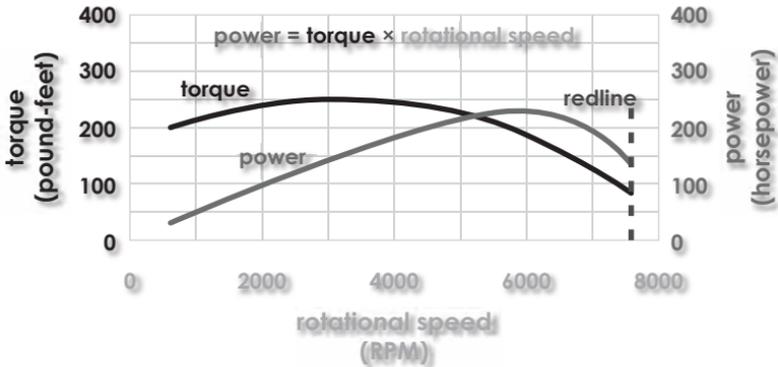
- ▶ Power is a function of the engine's rotational speed, while torque is not. As rotational speed increases, power increases linearly, while torque remains constant. It's too bad that real engines don't conform to this theoretical ideal, because if they did, we could just increase power indefinitely by simply increasing engine speed.

ideal torque and power curves



- ▶ In practice, the real-world torque curve for a typical automobile engine remains relatively flat through the middle range of engine speeds from about 2000 to 4000 rpm but drops off sharply at lower and higher speeds. On the high end, this deviation from the ideal is the inevitable result of mechanical friction, as well as the air resistance associated with the intake and exhaust flows. On the low end, the loss of torque is caused primarily by convective heat loss through the cylinder walls during the compression stroke. These losses cause reduced pressure in the cylinder, and—as the Otto cycle diagram tells us—lower pressure translates into lower torque.

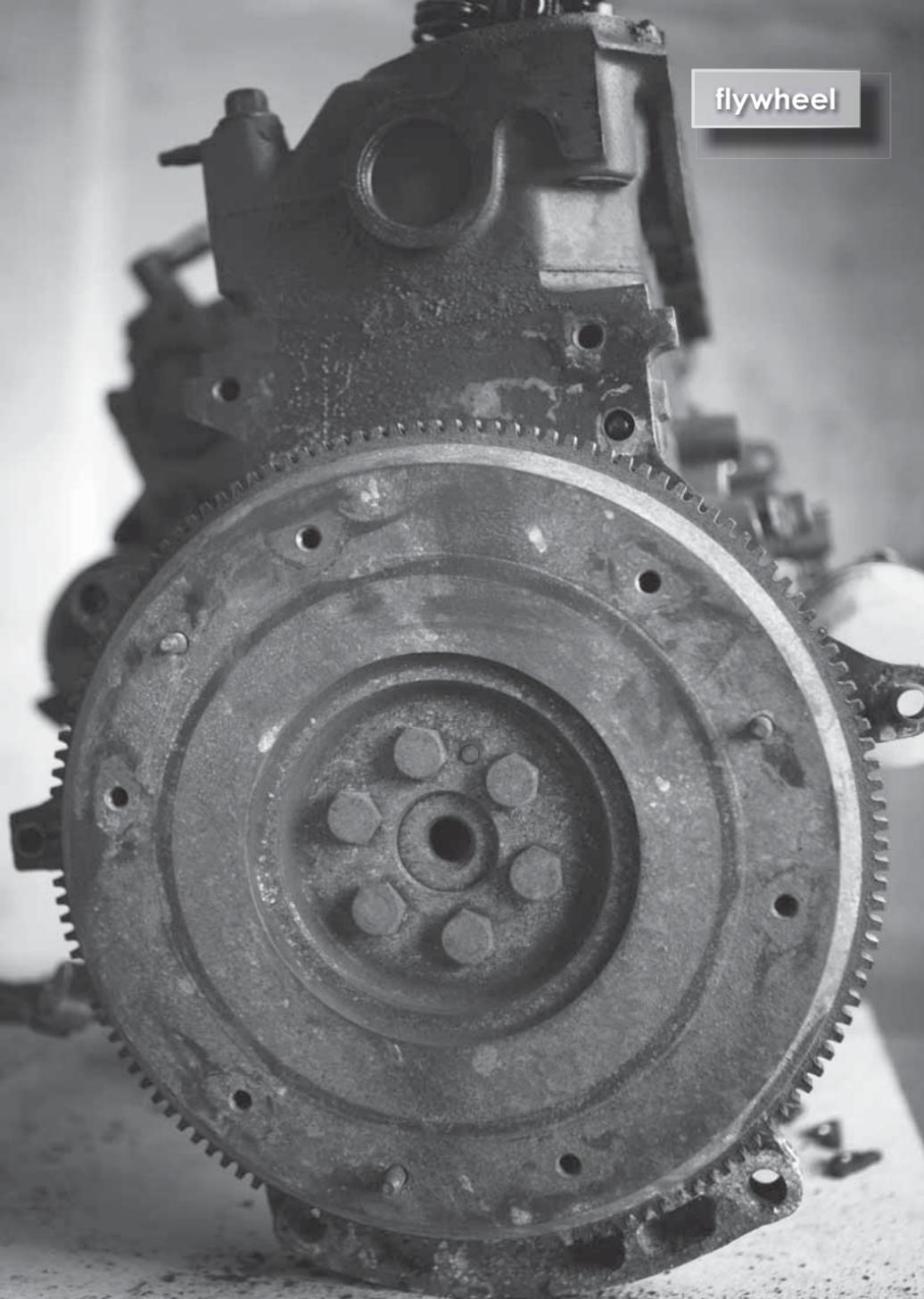
real-world torque and power curves



- ▶ Power = (torque) × (rotational speed), so the change in the torque curve from ideal to real world causes a similar change in the power curve. Power still increases with rotational speed, but only to a point, after which it drops off sharply. Beyond this point is the speed beyond which the engine is likely to self-destruct. At the low end, both the torque and power curves stop at around 800 rpm, because most internal combustion engines simply won't run at speeds much lower than this.
- ▶ These performance curves for a typical engine vividly illustrate the fundamental challenge associated with the design of the automotive drivetrain. When your car accelerates from a standstill to highway speed, its wheels accelerate through a range of speeds from zero to somewhat less than 1000 rpm. Through this entire range of vehicle performance, the engine should operate in the range from 800 to 6000 rpm, roughly 6 times higher. To translate high engine speed to low wheel speed, some sort of gearing is required. This gearing is the responsibility of the transmission.

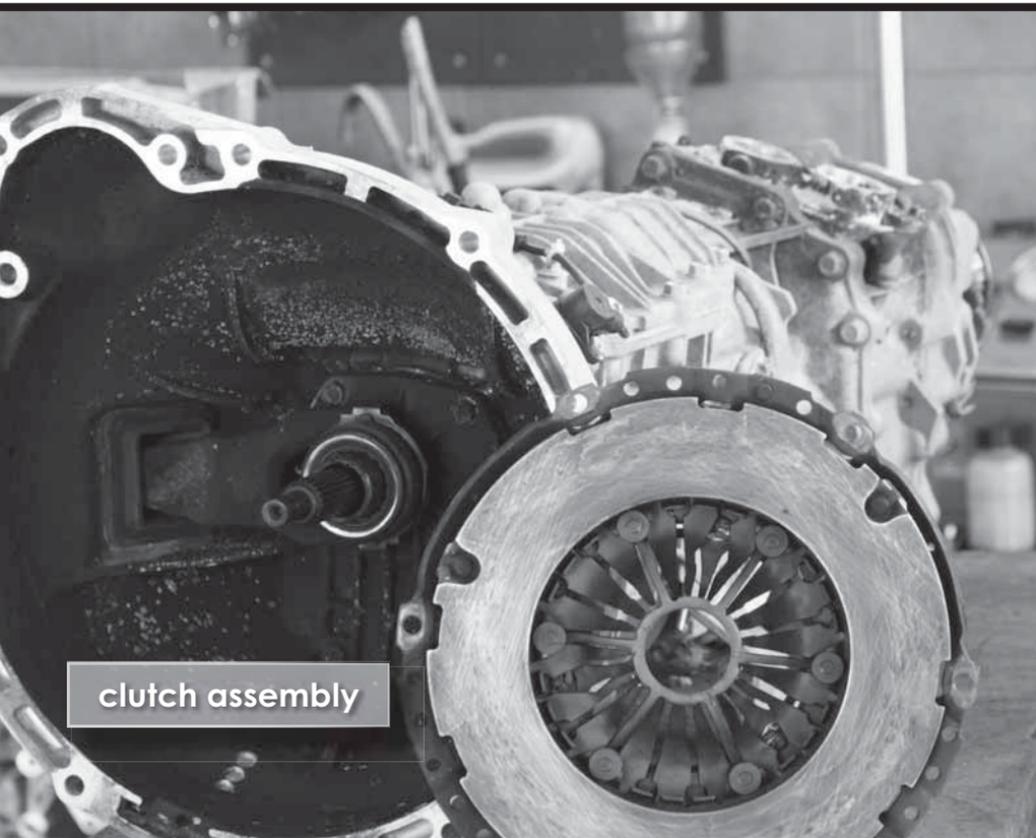
Gears and Transmission

- ▶ Gears are rotating disks with regularly spaced teeth that allow one gear to turn the other without slipping. Even though the gears might be of different sizes, the teeth are all the same size to ensure that they mesh properly as the gears turn.
- ▶ One purpose of gearing is to change the rotational speed of a shaft. Another is to change torque. At the point of contact where the gears mesh, each gear exerts a tangential force on the other. Based on Newton's third law—for every action, there's an equal and opposite reaction—we know that these forces are equal in magnitude.
- ▶ Gear sets of different sizes provide mechanical advantage—just like simple machines—and for gears, the mechanical advantage is equal to the **gear ratio**. Just as simple machines trade force for distance, these gears trade torque for rotation. Larger gears produce more torque but rotate more slowly; smaller ones are faster but produce less torque.
- ▶ There is no one-size-fits-all gear ratio that will provide adequate performance and fuel economy across a normal range of vehicle speeds. And that's why all automotive transmissions provide multiple gear ratios—which we know as first gear, second gear, third gear, and so on.
- ▶ The purpose of a transmission, then, is to keep the engine within its most efficient range of operation while providing adequate torque across the full range of vehicle speeds. This purpose is accomplished through a gearbox that provides multiple pairings of gears, each with different gear ratios. In first gear, a small driving gear turns a significantly larger driven gear, resulting in substantially increased torque and decreased speed. And successively higher gears provide for increased speed, at the expense of torque.



flywheel

- ▶ An internal combustion engine generates power through a succession of discrete impulses, each associated with the explosive combustion of fuel and air in one of the engine's cylinders. With each of these explosions, downward movement of the associated piston applies an impulsive torque to the crankshaft.
- ▶ To smooth out these discrete impulses, a heavy disk called the **flywheel** is fixed to the crankshaft. Flywheels have gear teeth on their outer rim because the teeth engage with the electric starter motor, which is used to start the engine.
- ▶ Affixed to the rear of the flywheel is the **clutch** assembly, which is used to disconnect the engine from the transmission on demand. The clutch is required for two reasons.



clutch assembly

- An internal combustion engine is incapable of running at significantly below its idle speed, typically around 800 rpm. Thus, when the vehicle is standing still, the engine must be disengaged from the drivetrain, or it will stall.
- Because of the tremendous forces that are being transmitted through the gearbox whenever it's in gear, the transmission must be physically disconnected from the engine to change gears.

TERMS

clutch: A device that is used to connect and disconnect a driving shaft from a driven shaft while one or both shafts are turning.

compression ratio: In an automobile engine, the ratio of the cylinder volumes, V_2 to V_1 , where V_1 is the volume at top dead center and V_2 is the volume at bottom dead center.

displacement: In an automobile engine, the volume swept by the piston as it moves from bottom dead center to top dead center.

flywheel: In an automobile drivetrain, a heavy disk that provides for steady rotation of the crankshaft in response to repetitive impulsive torques applied by the pistons.

gear ratio: The ratio of the numbers of teeth on two meshed gears. The gear ratio corresponds to the mechanical advantage of the gears.

Otto cycle: A thermodynamic cycle used to model the operation of an internal combustion engine.

reciprocating motion: Cyclic up-and-down or back-and-forth motion that is characteristic of a piston in a cylinder.

READINGS

Department of the Army, *Technical Manual 9-8000*.

Gillespie, *Fundamentals of Vehicle Dynamics*.

QUESTIONS

- 1 Based on the Otto cycle, what are three ways to increase the power of an internal combustion engine?
- 2 What is the purpose of a transmission? What is the purpose of a clutch?

The Drivetrain

Welcome to the third lecture in a four-lecture series on automotive engineering. In the previous lecture, you followed the transmission of mechanical power—which is torque multiplied by rotational speed—from the engine crankshaft through the flywheel-and-clutch assembly to the transmission gearbox in a front-engine rear-wheel-drive automobile. In this lecture, you will continue your journey rearward: from the gearbox, through the driveshaft, to the differential and drive wheels, where the rubber meets the road.

The Drivetrain

- ▶ The automotive driveshaft is normally a hollow tube made of steel or high-strength aluminum. Tubes are highly preferable to solid bars for two reasons: For a given amount of material, a tube resists torsion (or twisting) far more effectively, and the tube is also superior to the bar in bending.
- ▶ Another important characteristic of the driveshaft is its connection to the transmission output shaft at one end and to the **differential** at the other. The axle shafts, which extend laterally outward from the differential, are effectively part of the vehicle's **suspension** system.
- ▶ In a leaf-spring suspension, when the vehicle is moving, the leaf springs can flex quite a bit, causing the entire differential to move vertically, as well. Consequently, the driveshaft must be capable of changing its orientation without interrupting the transmission of power at a few thousand rpm.
- ▶ This flexibility is provided by **universal joints**, or U-joints, at both ends of the shaft. At the heart of a U-joint is a cross-shaped double axle, with each axle attached to one shaft by a hinge. This arrangement allows



differential

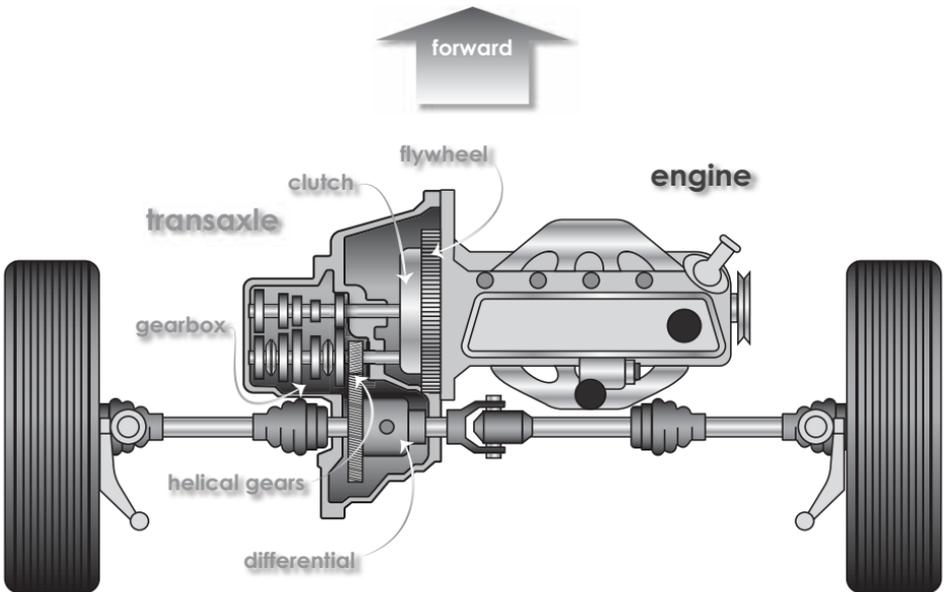
for rotation in two perpendicular directions. When one shaft rotates, the U-joint smoothly transmits power to the second shaft, even as the shaft's angle of orientation continuously changes.

- ▶ The differential is a mechanical device that performs three different functions simultaneously. It receives power from a single source—the driveshaft—divides it in half, and sends both halves to the perpendicular axle shafts; increases the gear ratio of the drivetrain by a factor of approximately 4 to 1; and allows the two drive wheels to rotate at different speeds when the vehicle is negotiating a turn.
- ▶ How does the differential accommodate this significant difference in rotational speed while continuing to deliver smooth power to both drive wheels?

- ▶ On the end of the vehicle's driveshaft, a small gear called a **pinion** engages with a larger **crown gear**. The crown gear's axis of rotation is perpendicular to the driveshaft. Through this mechanism, the differential achieves its first purpose of dividing input power into two perpendicular axle shafts.
- ▶ The pinion rotates about four times faster than the crown gear. This pair of gears, often called the **final drive**, also achieves the differential's second purpose of increasing the drivetrain's gear ratio.
- ▶ The differential's third purpose is performed by a mechanism called a **planetary gearset**. Its principal components are two sun gears, each fixed to one of the axle shafts; two planet gears, configured such that they can revolve around the sun gears; and a frame called the **planet carrier**, which holds the planet gears, is fixed to the crown gear of the final drive, and can rotate independent of the axle shafts.
- ▶ When the vehicle is driving straight ahead, the entire planetary gearset is basically just along for the ride. The planet gears don't rotate, and the sun gears and axles are spinning at the same rotational speed as the crown gear. But when the vehicle turns, the two wheels rotate at different speeds—and, as a result, the planet gears rotate to accommodate the different shaft speeds.
- ▶ The planetary gearset causes the average rotational speed of the two sun gears to always be equal to the rotational speed of the crown gear. Thus, the total power delivered to the two axle shafts doesn't change, but the allocation of power does, with the faster shaft receiving proportionately more power.
- ▶ At the ends of the two axle shafts are the final components of the automotive drivetrain: the drive wheels. They're also integral components of the suspension, steering, and braking systems.

Front-Wheel Drive

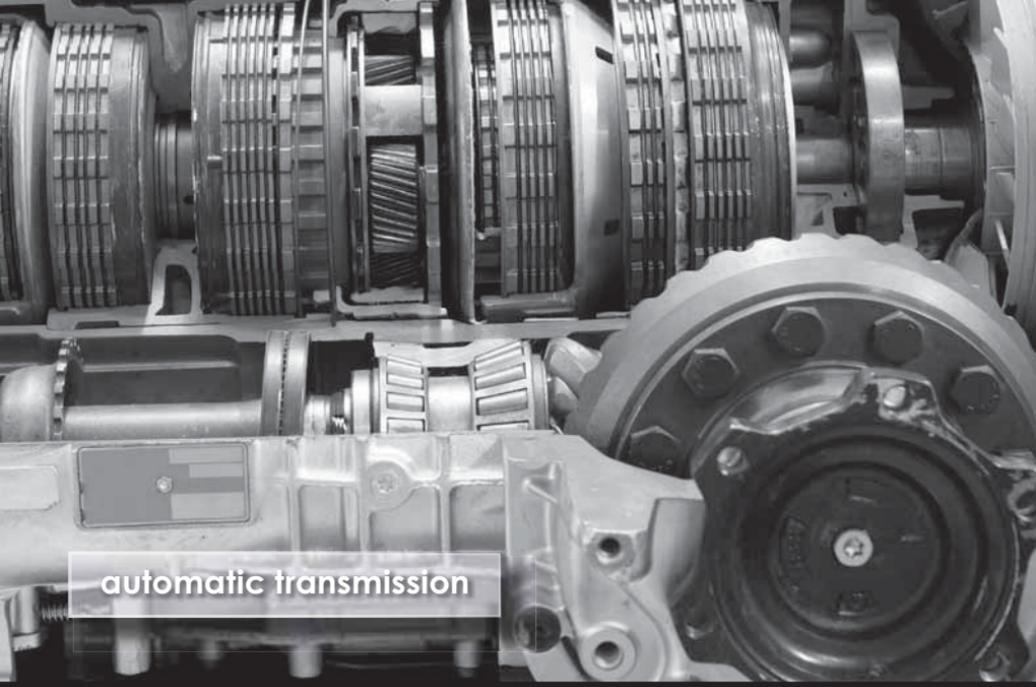
- ▶ As opposed to the drivetrain of a front-engine, manual-transmission, rear-drive automobile, the two most popular alternative configurations are front-wheel drive and the automatic transmission.
- ▶ In the typical layout of the engine and drivetrain in a front-drive manual-transmission car, the engine, flywheel, clutch, and gearbox are all essentially identical to the configuration of a rear-drive car, except that the entire unit is turned sideways.
- ▶ The other major difference is that in front-wheel drive, the transmission and differential are integrated into a single unit, properly called a **transaxle**. And the output shaft of the gearbox drives the differential directly, with no driveshaft.



- ▶ Front-wheel drive has several significant advantages over rear-wheel drive. Elimination of the driveshaft saves weight and thus improves fuel efficiency. The compact, transversely mounted engine-transaxle unit allows for a smaller engine compartment and a correspondingly larger passenger compartment. Space efficiency is further improved because the transmission, driveshaft, and differential can't impinge on either the passenger compartment or cargo compartment. Placing the engine directly over the drive wheels also improves **traction** and steering stability, particularly on slippery roads.
- ▶ Front-wheel drive does have its disadvantages, though. Anytime a vehicle accelerates, its weight shifts rearward. In a rear-drive car, this shift increases the traction of the drive wheels, which is why racing cars and other high-performance vehicles almost always use rear drive. In a front-drive car, this weight shift reduces the drive wheels' traction and can cause the tires to slip—an effect that's exacerbated if you're accelerating up a hill.
- ▶ Perhaps the most important disadvantage of front-wheel drive is that integrating power transmission and steering into a single axle increases mechanical complexity. For example, axle shafts must be connected to the drive wheel hubs through very sophisticated universal joints called constant-velocity joints, which provide steady transmission of power, even as the wheels pivot and move up and down.
- ▶ Still, the predominance of front-wheel drive in all but performance cars and large vehicles today suggests that the advantages of this configuration significantly outweigh the disadvantages in most circumstances.

Automatic Transmission

- ▶ The automatic transmission is a system that is fundamentally different from its manual counterpart and quite a bit more complex, too. An automatic transmission consists of three major components: a **torque converter**, a gear unit, and a **hydraulic control unit**.



- ▶ The torque converter is a fascinating device that serves essentially the same function as the clutch in a manual transmission: It allows the engine to keep running when the vehicle comes to a stop, and it cushions abrupt changes in the relative speeds of the input and output shafts during gear changes. The difference, of course, is that it must perform these functions without human intervention.
- ▶ The torque converter couples the engine to the transmission with a moving fluid. The device is composed of three main components: the impeller, turbine, and stator.
- ▶ At the heart of the gear unit is a planetary gearset. Similar to the gearset in the differential, it uses a central sun gear and two or more planet gears that can “revolve around the sun” on a rotating planet carrier. But unlike the differential gearset, this one has all gears rotating in the same plane, and it also includes an additional outer ring-shaped gear, called an **annular gear**.

- ▶ This gearset has a fascinating characteristic that makes it quite useful for transmissions. The mechanism has three main components—the annular gear, sun gear, and planet carrier—and any two of these three can be used for input and output if the third one is locked or constrained.
- ▶ The key feature of the planetary gearset is that all six possible configurations can be achieved simply by locking and unlocking components. Changes of configuration can be made instantaneously, without the interruption of power input, and the gears remain in mesh continuously.
- ▶ Taking advantage of this very powerful feature, one type of three-speed automatic transmission provides the four required gear ratios—three forward and one reverse—by linking two planetary gearsets together and then using a series of hydraulically operated clutches and brakes to lock and direct input power through different components of the two gearsets.
- ▶ The other key components of this system are two clutches and two **brake bands**, all of which are hydraulically actuated. When the forward clutch is engaged, it connects the **input shaft** to the annular gear of the forward planetary gearset. When the drive-and-reverse clutch is engaged, it connects the input shaft to the common sun gear.
- ▶ The brake bands are steel straps that, when pulled tight by hydraulic actuators, lock certain components of the planetary gearsets. The forward band is used to lock the sun gear, and the rear one is used to lock the planet carrier of the reverse gearset.
- ▶ The required gear ratios are achieved by using clutches and brakes to control which components of the planetary gearsets receive power and which are locked. In this regard, the modern trend has been to replace brake bands with clutches, because clutch engagement is generally faster and more precise.
- ▶ In part because of the complexity of the hydraulic control unit, some state-of-the-art transmissions have switched to electronic control systems that eliminate much, though certainly not all, of the hydraulic hardware.

TERMS

annular gear: A ring-shaped spur gear with teeth oriented inward, typically used as a component of a planetary gearset.

brake band: In an automatic transmission, a steel strap that, when pulled tight by hydraulic actuators, locks certain components of a planetary gearset.

crown gear: A large gear with teeth oriented perpendicular to the plane of the gear.

differential: A mechanical device that performs three different functions: allocating power from the driveshaft to two perpendicular axle shafts, increasing the gear ratio of the drivetrain, and allowing the two drive wheels to rotate at different speeds when the vehicle is negotiating a turn.

final drive: In an automotive differential, the pinion and crown gears.

hydraulic control unit: In an automatic transmission, a fluid-powered computer that uses pressurized transmission fluid moving through a series of valves to determine when each shift should occur and to execute the changes of gears.

input shaft: In an automobile drivetrain, a shaft that connects the engine to the transmission.

pinion: A small gear that is typically positioned on the end of a shaft.

planet carrier: In a planetary gearset, the fixture on which one or more planet gears are mounted.

planetary gearset: An arrangement of one or more sun gears, each of which rotates on a fixed shaft, and planet gears, which revolve around the sun gears.

suspension: In an automobile, a mechanical system that supports the weight of the vehicle, provides road isolation, provides roadholding, and prevents excessive body roll.

torque converter: In an automatic transmission, a device that allows the engine to keep running when the vehicle comes to a stop and that cushions abrupt changes in the relative speeds of the input and output shafts during gear changes. The three main components of a torque converter are the impeller, turbine, and stator.

traction: The accelerating, braking, and turning forces generated at the interface between a vehicle tire and the surface on which it is rolling.

transaxle: An automotive transmission and differential integrated into a single unit.

universal joint: A mechanical connection between two shafts that allows the transmission of torque between shafts, even when one shaft is angled with respect to the other.

READINGS

Department of the Army, *Technical Manual 9-8000*.

Gillespie, *Fundamentals of Vehicle Dynamics*.

QUESTIONS

- 1 What are the three principal functions of a differential?
- 2 Why might a standard automotive differential not function properly on an icy road surface? (Hint: The limited-slip differential is a technological solution to this problem.)

Suspension, Steering, and Braking

You might have 400 cubic inches under the hood of your car, but all the automotive power in the world is useless if you can't keep the vehicle between the white lines. This lecture will wrap up the four-lecture series on automotive engineering by examining the three systems that help you stay in control: suspension, steering, and braking. And the lecture will begin with a technology that's vital to all three systems—your tires.

Tires

- ▶ The pneumatic tire is a composite structure made of multiple layers of fabric, called plies, often reinforced with steel belts and wires, all embedded in rubber. The rubber binds all of these layers together, adds flexibility, and makes the structure airtight—so that the void inside can be filled with air at high pressure.
- ▶ The reinforcing plies are usually made of polyester cord, and their orientation is the principal basis for classifying tires. The plies of **radial tires** are oriented in the radial direction, perpendicular to the tread. In **bias-ply tires**, the cords are oriented in an alternating diagonal pattern. Today, radial tires are used almost exclusively, because of their better steering control, longer tread life, and lower rolling resistance.
- ▶ In an automotive system, tires serve three main purposes: They support the vehicle's weight, absorb minor shocks due to irregularities in the road surface, and provide traction—transmitting all acceleration, braking, and turning forces between the vehicle and the road.
- ▶ When air is contained inside a tire under pressure, the pressure acts perpendicular to the tire's inner surface. When a car's weight acts downward on one of its wheels, the tire flattens a little on the bottom,

where it makes contact with the ground, and the direction of the pressure remains perpendicular to the flattened surface. The flattened area on the tire is called the contact patch.



- ▶ The tire pushes downward on the ground only at the contact patch. To maintain equilibrium, the ground pushes back with exactly the same pressure. This upward pressure acting over the contact area constitutes a normal force, which counterbalances the weight that's being applied to the wheel. The magnitude of this normal force is simply the pressure times the contact area.
- ▶ Contact patches do a lot more than just support the car's weight. We tend to think of the engine as the driving force that moves a car forward, but when we look at the vehicle externally, the only thing moving it forward is the traction force, which is really just the friction developed at the contact patch of the drive wheels.

Suspension

- ▶ There are two basic types of suspension systems. A conventional solid-axle system consists of a one-piece axle. In a common suspension configuration, the solid axle is fixed to a pair of steel leaf springs, though there's another common configuration called the trailing arm. Regardless of how it's attached to the vehicle chassis, the solid axle has an inherent disadvantage: the dynamics of its two wheels are interdependent. When one wheel hits a bump, the solid axle rotates, and the other wheel must necessarily rotate along with it.

- ▶ In an **independent suspension system**—so named because the motion of each wheel is completely independent of all the others—when one wheel hits a bump, the others are unaffected. A multi-link system is a particular type of independent suspension that is named for two linkages that are mounted to the chassis and are free to pivot vertically. Because the linkages are parallel, they keep the wheel essentially vertical through its full range of motion—a significant advantage of this system. Between the two linkages is a coil spring, which performs the same function as the leaf spring in a solid-axle suspension.
- ▶ For many years, it was common for automobiles to mix and match suspension systems, with an independent suspension up front and a solid axle in the rear. This was particularly true for rear-wheel-drive vehicles, because the simpler, more robust leaf-spring and trailing-arm systems are well suited for transmitting large traction forces from the drive wheels to the chassis.
- ▶ But today, nearly all cars use four-wheel independent suspensions because of their lighter weight and better performance characteristics. The solid rear axle is found almost exclusively on trucks and large SUVs.
- ▶ Regardless of configuration, the suspension system has four principal purposes.
 - It supports the weight of the vehicle, its occupants, and its cargo—and distributes that weight as evenly as possible to all four wheels.
 - As the vehicle moves across bumps and potholes, the **springs** absorb the impacts caused by these irregularities. This function, called **road isolation**, is important not only for the vehicle’s occupants, but also for all of the sensitive mechanical and electronic systems.
 - Not only do the springs isolate the vehicle from the bumps, but they also force the wheels back down onto the road surface after passing over each bump. This ability to follow the contours of the road surface is called **roadholding**, and it’s critical for both traction and control.

- Anytime a vehicle accelerates, it pitches rearward; anytime it decelerates, it pitches forward. And anytime it makes a turn, it rolls toward the outside of the curve. These pitching and rolling motions are inevitable: They occur because the forces that cause a car to accelerate, decelerate, and turn are all applied down at the level of the roadway—at the contact patch between the tires and the road surface—while the vehicle’s center of mass is significantly above the road surface. If these pitching and rolling motions are too large, they can lead to loss of control. Thus, an important purpose of the suspension system is to prevent these motions from becoming excessive.

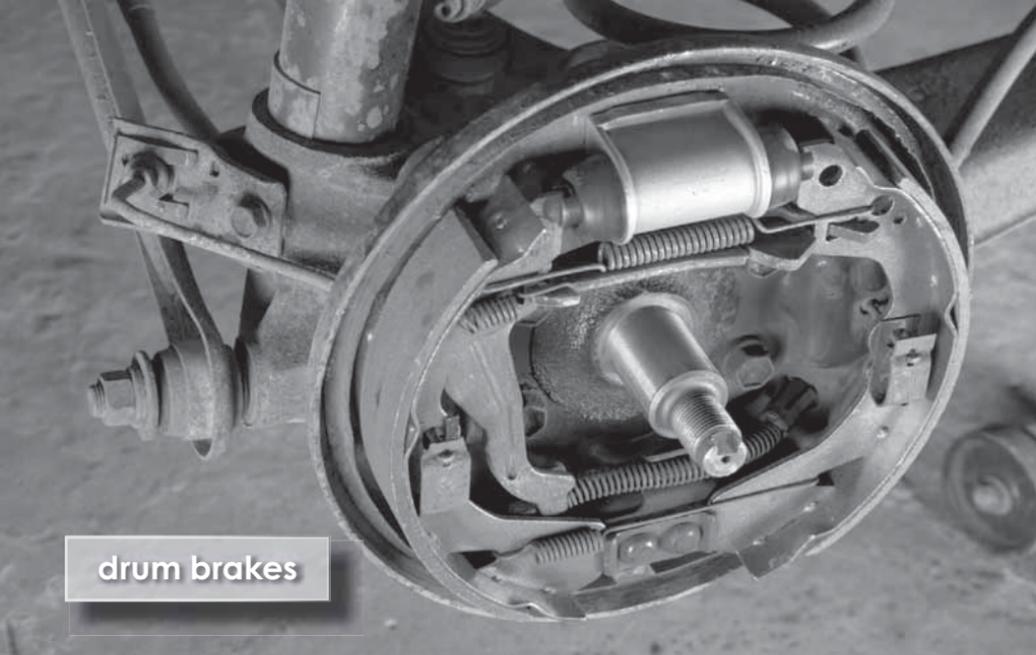
Steering

- ▶ The purpose of your car’s steering system is to convert the rotation of your steering wheel into the rotation of your front wheels, with an appropriate degree of mechanical advantage. Today, most cars use a type of system called rack-and-pinion steering.
- ▶ The steering wheel rotates the steering column, which has a pinion gear mounted on its end. The pinion is engaged with a toothed horizontal bar called the rack. As the pinion rotates, the rack shifts to the left or right, and this lateral motion pivots the front wheels through a mechanical linkage consisting of tie rods and steering arms.
- ▶ The steering wheel, combined with the rack-and-pinion mechanism, provides considerable mechanical advantage; however, many modern steering systems make it even easier on us by adding a hydraulic power assist so that we need to apply even less force at the steering wheel.
- ▶ When you turn your steering wheel, your two front wheels don’t rotate through the same angle; your outer and inner wheels follow two different circular arcs when your vehicle negotiates a turn. Because the outside arc has a larger radius, your outside front wheel should turn a bit less than the inside wheel for a given turn.

Braking

- ▶ The two principal types of vehicle braking systems are **disk brakes** and **drum brakes**. Disk brakes are generally considered to be the superior technology, and all modern cars use them for at least their front wheels. Some cars still use drum brakes on their rear wheels as a cost-saving measure, though four-wheel disk brakes are becoming increasingly common.
- ▶ In a disk brake, a metal disk is rigidly fixed to the rotating axle. A caliper, which fits around the disk, contains two hydraulically activated brake pads, one on each side. When you press the brake pedal, pressurized hydraulic fluid forces the brake pads inward against the disk. The brake pads apply a pair of compressive normal forces to the disk, generating friction that slows the rotation of the disk and axle.





drum brakes

- ▶ Extremely large friction forces are required to bring a car to a halt quickly from high speed. When this happens, all that kinetic energy is transformed into heat at the interface between the brake pads and the disk. This heat must be dissipated rapidly to prevent a phenomenon called **brake fade**.
- ▶ This is the primary reason why disk brakes are inherently superior to drum brakes—because most of the disk is exposed to the air. Thus, the heat dissipates more readily. This prolonged exposure to high friction forces also causes the brake pads to wear out eventually.
- ▶ In a drum brake, a steel drum is fixed to the rotating axle, and a pair of brake shoes inside the drum are fixed to the suspension system—so that they don't rotate with the axle. These shoes are forced outward by hydraulic pressure to stop the car. The brake shoes have abrasive linings, which make contact with the inside of the drum to generate the required friction force.

- ▶ Drum brakes are inferior to disk brakes, because heat builds up inside the drums and isn't as easily dissipated. Nonetheless, drum brakes are still used on the rear wheels of many vehicles, because they're cheaper and because the front wheels make a significantly greater contribution to stopping the car due to the forward shift in the vehicle's weight distribution during deceleration.
- ▶ An advantage of drum brakes is that the brake shoes can be activated mechanically as well as hydraulically. Mechanical activation must be used for the car's hand brake; thus, in a car with four-wheel disk brakes, a separate hand brake mechanism must be provided, at increased cost.
- ▶ One of the most important enhancements to automotive safety over the past few decades has certainly been the advent of the **antilock braking system (ABS)**, which is intended to prevent your wheels from locking up during hard braking. ABS uses electronic sensors to detect when a wheel is about to lock up and then releases and reapplies the brakes in short pulses many times per second, resulting in a shorter stopping distance and better control, particularly on slick surfaces.

TERMS

antilock braking system (ABS): An automotive braking system that enhances traction and control by using electronic sensors to detect when a wheel is about to lock up and then releasing and reappling the brakes in short pulses, many times per second.

bias-ply tires: A vehicle tire with its internal reinforcing plies oriented in an alternating diagonal pattern.

brake fade: The tendency of automotive brakes to lose effectiveness due to the buildup of heat.

disk brake: An automotive braking system in which a pair of hydraulically operated brake pads are forced against a disk to reduce the speed of the vehicle.

drum brake: An automotive braking system in which a pair of hydraulically operated brake shoes are forced against the inner surface of a drum to reduce the speed of the vehicle.

independent suspension system: An automotive suspension system in which the road-induced motion of one suspension unit does not affect the motion of the other suspension units.

radial tire: A vehicle tire with its internal reinforcing plies oriented in the radial direction.

roadholding: The ability of an automotive suspension system to keep the tires in contact with the road surface as the vehicle moves.

road isolation: The ability of an automotive suspension system to absorb the impacts caused by irregularities in the road surface.

spring: (1) A source of water occurring where an aquifer intercepts the ground surface. (2) A mechanical device that provides a resisting force proportional to its deformation in either tension or compression.

READINGS

Department of the Army, *Technical Manual 9-8000*.

Gillespie, *Fundamentals of Vehicle Dynamics*.

QUESTIONS

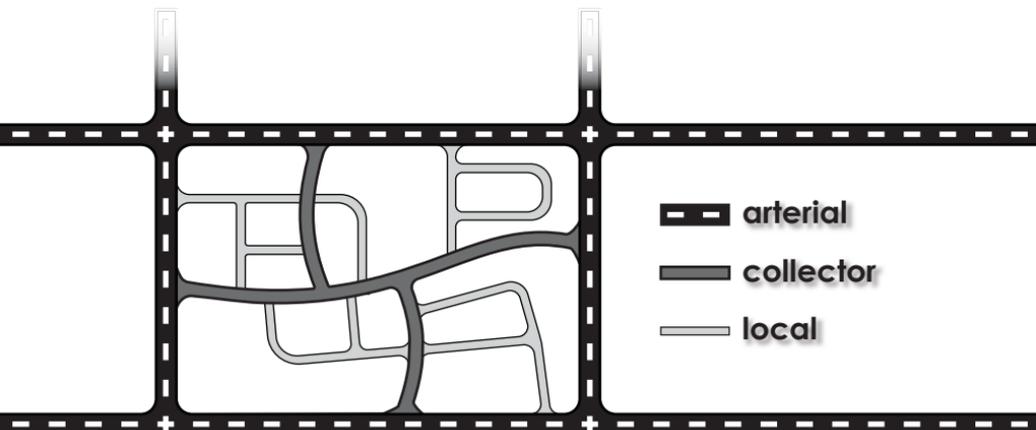
- 1 Why are the drive wheels of a front-wheel-drive car more likely to slip during acceleration than the drive wheels of a rear-wheel-drive car?
- 2 Why does an independent suspension system generally result in better control than a solid-axle system? Why does it result in a more comfortable ride?

Highway Engineering

Since the dawn of civilization, transportation systems—and roads in particular—have been fundamental to economic development and human quality of life. Today, roads facilitate the movement of raw materials to factories; manufactured and agricultural products to markets; and people to the places where they live, work, shop, and play. In this lecture, you will examine many of the major considerations involved in designing a highway. As you will discover, many manifestations of highway design are integrated elements of an engineered system that has achieved a time-tested balance of speed, safety, and comfort.

Roads

- ▶ For the purpose of engineering design, roads are classified according to their location—either urban or rural—and their function—**arterial**, **collector**, or **local**.
 - The function of an arterial is to provide long-distance mobility, facilitating movement from one region or city to another.

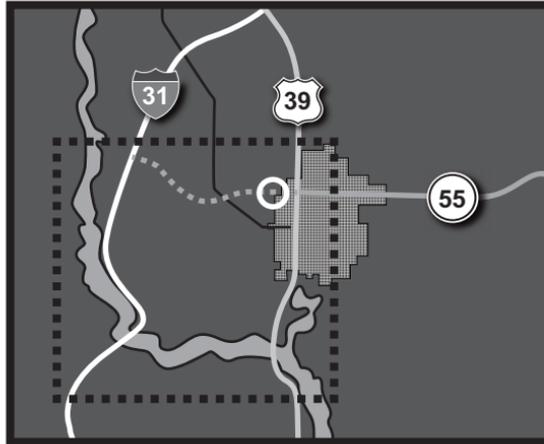


- At the opposite end of the spectrum, local roads provide access within residential areas, commercial districts, and so on.
- In between, collectors are designed to convey traffic between the local roads and arterials.
- ▶ These classifications are vital to the design process, because they dictate many of a road's physical characteristics. Principal arterials are typically divided highways with relatively shallow gradients and gradual curves. But the price of speed is limited access; we can only enter and depart from these highways at specially constructed **interchanges**.
- ▶ Major collectors are typically characterized by large numbers of controlled **intersections**. And minor roads are sometimes designed deliberately to discourage both through traffic and high speed.
- ▶ Roads design is one facet of transportation engineering, a branch of civil engineering. Transportation engineering is a broad field that also includes the analysis and design of airports, mass-transit systems, pipelines, and ports. As such, automotive transportation systems are typically handled by two groups of specialists: highway engineers, who design roads; and traffic engineers, who manage the safe and efficient movement of vehicles on roads through such measures as intersection design, signaling, lane markings, and signage.
- ▶ A road is an engineered system, the design of which derives from three main sources: the characteristics of drivers, the characteristics of vehicles, and the characteristics of the roadway itself. To understand how these three factors come into play, we need to examine the process of highway design.
- ▶ U.S. Route 39—a north-south arterial—was built 60 years ago, and over time, a major metropolitan area grew up along it. In the 1990s, U.S. 39 was upgraded to become Interstate 31, and the new highway was routed around the metropolitan area to the west to avoid congestion.

- ▶ To accommodate increasing demand for access to I-31, the State Department of Transportation has decided to extend an east-west arterial—State Route 55—from the city to the interstate. This new highway will traverse 8 miles of mostly undeveloped rolling terrain and thus will be classified as a rural arterial.

In addition to its two connections to existing highways, it will have one additional interchange on the west side of the metropolitan area.

- ▶ Our job is to design this new highway. Our design will be based on an extensive regional traffic study, which was conducted to determine the anticipated future **traffic volume** and the anticipated proportions of cars and trucks that will use the new highway. This study included vehicle counts of traffic entering and leaving the region by all possible routes, as well as extensive interviews with drivers to determine the origins, destinations, and purposes of their trips.
- ▶ Based on the results of this study, we've determined that the new highway should be designed to accommodate a traffic volume of 25,000 vehicles per day. This number—called the average daily traffic (ADT)—can be used to determine how many traffic lanes the highway will need. In this case, it turns out that our highway will need four lanes to meet a reasonably free-flow level of service.
- ▶ With the number of lanes determined, we're ready to execute the actual highway design in six major phases.
 - Determining the **alignment** of the roadway—that is, the specific path it will take across the ground.



- Defining the **cross-section** configuration, which includes such factors as the widths and slopes of the traffic lanes, shoulders, and embankments.
- Designing the pavement, to include the upper surface of asphalt or concrete and the underlying layers of compacted fill.
- Collaborating with our structural engineering colleagues to design any required bridges and interchanges.
- Collaborating with our water resources engineering colleagues to design the drainage system.
- Planning signage and fencing to control traffic flow and enhance safety.

The Alignment of the Roadway

- ▶ The process of defining the alignment can be quite challenging, because so many factors are likely to influence this decision, including the topography and soil conditions along the route; the length of the route; the need to cross or avoid obstacles, such as population centers and rivers; the need to cross railroads and other roads; the need for interchanges at specific locations; the construction cost; acquisition of the right-of-way; and environmental impact.
- ▶ Because these criteria often conflict with each other, there will probably be several feasible alignments and no clear best choice. Thus, the process of determining the optimal alignment is likely to involve fully developing several design alternatives and then comparing their respective costs and benefits.
- ▶ There is a set of detailed guidelines for the geometric design of highways published by a standards organization called the American Association of State Highway and Transportation Officials (AASHTO).

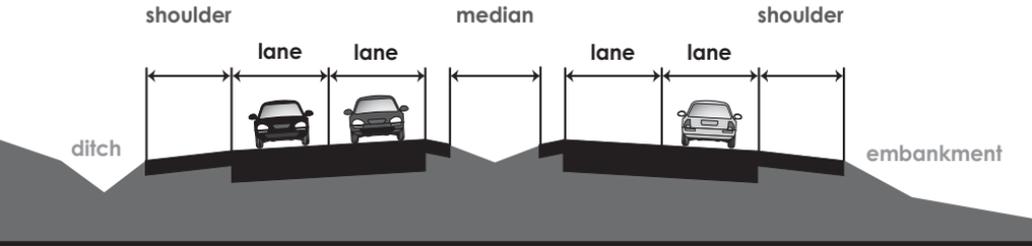
These guidelines include separate specifications for both the horizontal alignment—the route as viewed from above—and the vertical alignment—the highway profile, viewed from the side.

- ▶ In defining the highway alignment, we need to make preliminary decisions about the interchanges at each end, because the elevation of the roadway at these points will be dictated, to some degree, by the types of interchanges we use.
- ▶ In defining the alignment, we must also identify any required bridges along its length.
- ▶ A highway invariably interrupts natural drainage patterns, so a given alignment invariably dictates a unique drainage system design.
- ▶ For a large-scale highway project, we would likely generate several designs of viable alignment alternatives. Then, we would compare alternatives and select the optimum one based on factors such as length, construction cost, right-of-way acquisition, environmental impact, and so on.
- ▶ In regions with different topography, the design process can be different. In mountainous terrain, for example, alignment is usually controlled almost entirely by maximum gradients. In flat regions, horizontal alignment typically controls the design, and in urban areas, the highway's impact on existing development usually dominates all considerations of topography.

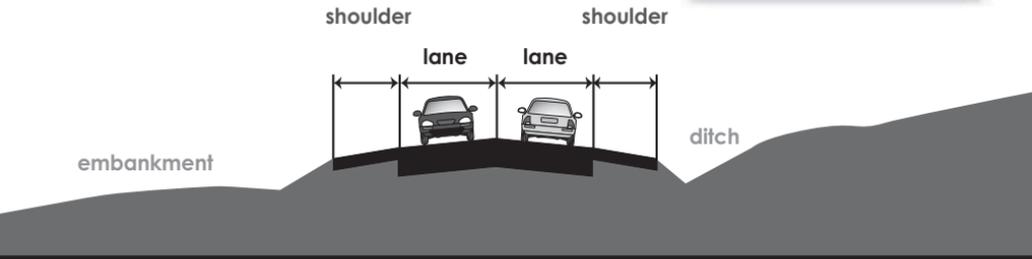
The Cross-Section Configuration

- ▶ A highway's cross-section configuration includes the shape and dimensions of the road surface, shoulders, median, drainage ditches, and embankments. The AASHTO standard provides detailed guidelines for these features. For example, the standard lane width for principal arterials is 12 feet, and shoulders are generally 10 to 12 feet wide.

four-lane divided highway



two-lane road

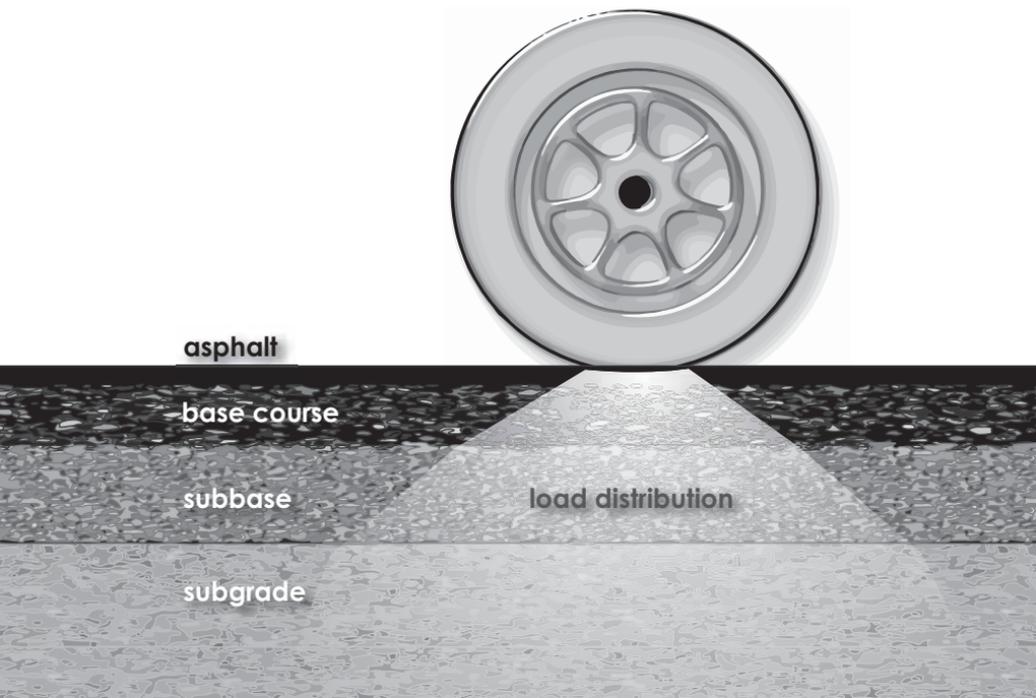


- ▶ Although two-lane roads typically have a slight crown to drain rainwater laterally from the road surface toward both sides, divided highways use a uniform cross-slope that directs all of the runoff in one direction for all lanes on either side of the median. The crowned shape isn't used for divided highways, because it can lead to loss of control during high-speed lane changes.
- ▶ When the lanes, shoulders, median, ditches, and embankments are all taken into account, the typical right-of-way for a major divided highway is about 250 feet wide and can be much wider when topographic conditions dictate a wider median. Thus, a typical freeway is nearly as wide as a football field is long.

The Pavement

- ▶ When you see the term “pavement,” you probably think of the hard surface on which your car rides. But from an engineering perspective, this surface is really just the icing on the cake. What’s underneath is at least as important.
- ▶ There are two principal types of pavement: **flexible pavement**, which typically uses an asphalt surface, and **rigid pavement**, which uses concrete.
- ▶ A typical cross-section of a flexible pavement could be upward of 2 feet thick. At the very bottom is the subgrade, usually natural soil that has been compacted by a **roller** to improve its strength. Above the subgrade are two more layers of compacted fill, called the subbase and base. In general, the subbase uses higher-quality soil than the subgrade, and the base uses higher-quality soil than the subbase.
- ▶ There are four basic types of soil: gravel, sand, clay, and silt. Of these, gravel and sand are preferred for most forms of construction, because they are stronger, are less susceptible to long-term settlement, and drain well.
- ▶ The optimum soil for load bearing is called a well-graded gravel, a mixture of granular particles ranging from relatively large chunks of angular stone down to small grains of sand. When this mixture is properly compacted, the smaller particles fill the voids between the larger particles, and the whole assembly locks together into a structure that’s almost as strong as concrete.
- ▶ The challenge is that, for the sake of economy, most road-construction projects are constrained to use locally available fill, and the perfect well-graded gravel is seldom available in the huge quantities required for a highway.

- ▶ Thus, the typical flexible pavement uses a layered structure with the highest-quality fill on top and relatively low-quality stuff below. The top layer is asphalt—a thick petroleum product mixed with gravel—which provides protection from the elements and resistance to the abrasive effects of vehicle traffic, but relatively little structural strength. That’s the responsibility of the compacted layers below.
- ▶ Conversely, in a rigid pavement, most of the structural strength is in the uppermost layer—usually a thick slab of concrete—often reinforced with steel bars. There’s still a layer of compacted fill below to serve as a foundation and to provide drainage, but the concrete does most of the heavy lifting.
- ▶ A rigid pavement is somewhat more expensive than a flexible pavement, but it has a significantly longer useful life, requires less maintenance, and is less susceptible to problems associated with settlement of the subgrade. As such, rigid pavements are typically used for major high-speed arterials.



TERMS

alignment: In highway design, the path a highway takes across the ground. A road alignment includes both vertical and horizontal components.

arterial: A road that provides long-distance mobility, facilitating movement from one region or city to another.

collector: A road that conveys traffic between the local roads and arterials.

cross-section: The geometric shape of the face created by making a hypothetical cut perpendicular to the longitudinal axis of a structural element, roadway, etc.

flexible pavement: A road structure typically consisting of a layer of asphalt placed on a layered base of compacted fill.

interchange: In traffic engineering, an intersection at which traffic streams cross at two or more different levels. Also called a **grade-separated intersection**.

intersection: A traffic structure at which two or more streams of traffic cross each other, with drivers typically having the option to continue on their present route or to switch from one stream to another.

local road: A road that provides access within residential areas, commercial districts, etc.

rigid pavement: A road structure that typically consists of a reinforced concrete slab placed on a layer of compacted fill.

roller: A structural support that permits rotation and horizontal movement but restrains vertical movement.

traffic volume: In highway design, the amount of traffic on a highway, measured in vehicles per day.

READING

Garber and Hoel, *Traffic and Highway Engineering*.

QUESTIONS

- 1** Explain the concept of balanced earthwork. Can you see evidence of design for balanced earthwork in a highway near your home?
- 2** Why do major arterial highways usually use rigid pavements, rather than flexible pavements?

Traffic Engineering

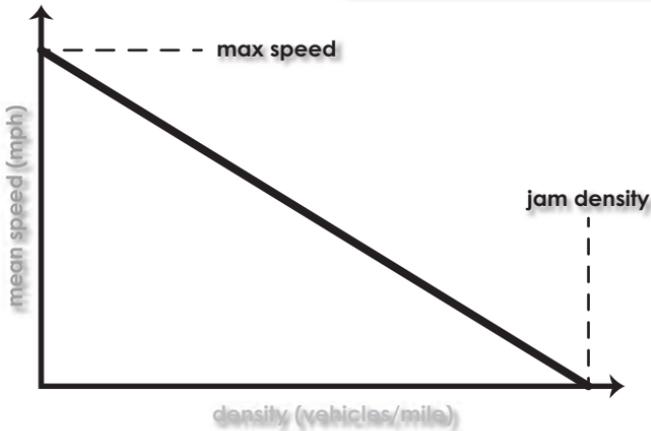
This lecture shifts in focus from the work of the highway engineer, who designs the geometric configuration and underlying structural support of major roads, to the work of the traffic engineer, who specializes in facilitating the safe and efficient movement of vehicles and pedestrians within a road system. Traffic engineers apply the scientific study of traffic flow to the design of roads, intersections, and traffic control. They're principally responsible for the geometric design of intersections, sidewalks, crosswalks, and bike paths, as well as traffic control markings, signs, and signals. They're also extensively involved in conducting investigations to improve traffic safety.

A Scientific Theory of Traffic Flow

- ▶ What does a scientific theory of traffic flow look like? One typical example is a theoretical mathematical model governing **traffic flow**, **traffic density**, and **mean speed**.
- ▶ Traffic flow is the hourly rate at which vehicles pass a specific point on a highway, measured in vehicles per hour. Density is the number of vehicles traveling on a specific length of highway at a particular instant in time, measured in vehicles per mile. Mean speed is defined as the average speed of all vehicles passing a point on a highway within a specified period of time, measured in miles per hour.
- ▶ All three of these quantities are mathematically related by the following equation: $\text{flow} = \text{density} \times \text{speed}$. The units in this equation work out consistently: $(\text{vehicles}/\text{hour}) = (\text{vehicles}/\text{mile}) \times (\text{miles}/\text{hour})$.
- ▶ To develop a usable theoretical model of traffic flow, we must also assume a theoretical relationship between any two of these three quantities. One common approach, called the Greenshields model, assumes a linear relationship between density and mean speed.

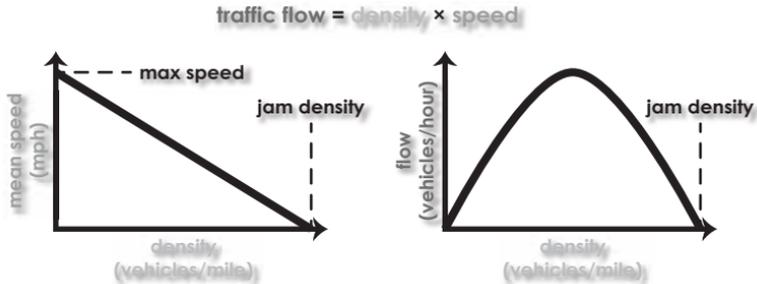
- ▶ The maximum speed that's possible on a given highway can only be attained when the traffic density is extremely low. As density increases, vehicles start constraining each other's movement, and their average speed decreases. Greater density continues to cause further speed reductions, until the traffic stream comes to a standstill. This is called the jam density.

the Greenshields model



- ▶ Based on this theoretical model, we can use the equation $\text{flow} = \text{density} \times \text{speed}$ to derive the corresponding graph of flow versus density, which turns out to be a parabolic curve. At low density, traffic flow is also low. As density increases, flow increases—but only to a point. At a critical traffic density, the curve peaks and then begins to drop off.
- ▶ Traffic becomes so dense that everyone slows down. Cars in the right-hand lane stack up behind slower vehicles, but they can't change lanes to pass, because the left-hand lane is already filled with vehicles. This is called congested flow—and as even more vehicles feed into the flow from on-ramps, increasing density drives down both speed and flow, until everything comes to a halt at the jam density.

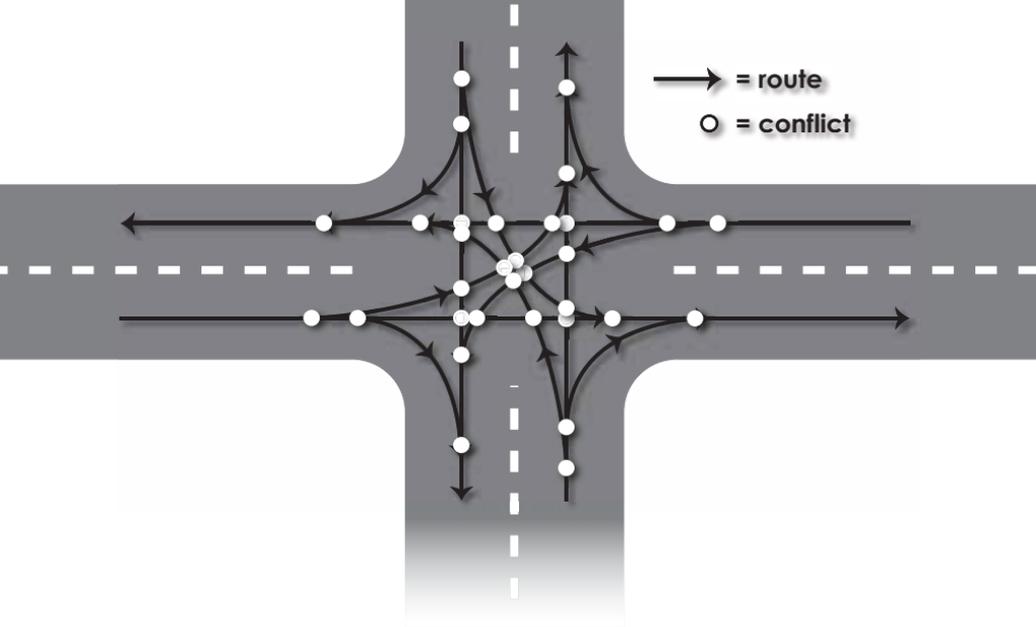
fundamental diagram of traffic flow



- ▶ The fundamental diagram of traffic flow is a beautiful example of the mathematical approach that underlies traffic engineering. And this theoretical tool has a variety of important practical applications, including rating highways for capacity, predicting traffic jams, and analyzing the adverse effects of traffic disturbances, such as lane closures.

Intersections

- ▶ To a large degree, the performance of our roads is dictated by intersections, because the volume of traffic that most intersections can handle is less than the capacity of the connected roadways. Most crashes happen at intersections, as well. For these reasons, intersections tend to have a dominant influence on our driving experience—for better or for worse.
- ▶ At the most fundamental level, an intersection involves two or more streams of traffic crossing each other, with drivers typically having the option to continue on their present route or switch from one stream to another. The combined effects of intersecting traffic streams and fallible human drivers making decisions create many possibilities for conflicts between vehicles.



- ▶ Conflicts are points at which two vehicles moving in different directions might collide with each other. Thus, every conflict is a potential crash. The principal goals of intersection design are to minimize these conflicts while also facilitating traffic flow, consistent with the physical constraints of the site and available funds. These goals and constraints often conflict with each other, so every intersection design represents a unique compromise between competing criteria.
- ▶ Intersections come in two types: **at-grade intersections**, which have all roads connecting at the same level; and **grade-separated intersections**, or interchanges, which have routes crossing at two or more different levels. Grade separation invariably eliminates many potential conflicts between vehicles; however, its most common purpose is to facilitate unconstrained traffic flow on at least one of the intersecting routes.

- ▶ Interchanges can be built in an amazing variety of configurations to accommodate different kinds of traffic requirements and constraints.
 - A diamond interchange is typically used when a freeway intersects with a minor road. Through traffic on the freeway is unconstrained; however, as a minimum, controlled intersections are required where the two freeway off-ramps meet the minor road. A serious disadvantage of this configuration is the possibility of a driver making a wrong turn onto a ramp and entering the freeway in the wrong direction. Well-designed diamond interchanges use signs, pavement markings, and median structures to reduce the probability of such potentially disastrous events.
 - A cloverleaf interchange is typically used when there are two divided highways and allows unconstrained through traffic on both intersecting routes, while also permitting eight possible turning

An aerial photograph of a diamond interchange. A multi-lane highway runs vertically through the center of the image. A smaller road crosses the highway at a 90-degree angle, forming a diamond shape. The interchange is well-designed with clear lane markings and a median. A white semi-truck is visible on the highway, and a car is on the crossing road. In the background, there are some buildings and a parking lot. A semi-transparent white box with the text "diamond interchange" is overlaid on the left side of the image.

diamond interchange



movements without stopping. At the on-ramps, the merging of these vehicles into the main traffic streams is generally controlled only by yield signs.

- A trumpet interchange is a variation on the cloverleaf that works just like a cloverleaf but is much simpler, because there's no through traffic on one of the two main highways. Thus, rather than eight possible turning movements, the trumpet only has four.
- ▶ From a traffic engineering perspective, the cloverleaf interchange has two significant shortcomings. To facilitate continuous traffic flow, the four “leaves” of the cloverleaf must have a relatively small turning radius—and, thus, vehicles must reduce speed significantly to negotiate the curve. Lower speed means reduced flow. Moreover, having just decelerated for the tight curve, these same vehicles must now accelerate rapidly for their upcoming merge into the high-speed flow of through traffic, resulting in significant potential for conflicts between vehicles.

- ▶ Both of these inherent problems have been very effectively addressed in the directional interchange, which is now used wherever possible for the intersection of two freeways. The characteristic feature of all directional interchanges is the flyover ramp, which makes a left turn by passing over or under the main freeways. The very large turning radius of these ramps allows vehicles to move from one traffic stream into the other with little or no reduction in speed. The directional interchange also eliminates the conflict between on- and off-ramps that occur with the cloverleaf. The off-ramps exiting from the freeway are upstream of the on-ramps feeding into the same route.
- ▶ The disadvantage of the directional interchange is cost. Not only do these large-radius curves occupy a huge tract of land, but a large proportion of any directional interchange also consists of multi-span bridges.
- ▶ The key distinguishing characteristic of the second major category of intersections—the at-grade intersection—is that an area of road surface is shared by two or more roads. Within this area, streams of traffic are able to change from one route to another at the drivers' discretion, greatly increasing the potential for conflicts.
- ▶ Traffic engineers classify at-grade intersections as multi-leg, four-leg, and T intersections. When designing at-grade intersections, traffic engineers consider six major elements of intersection design.
 - **Horizontal alignment.** Roads should intersect at as close to 90° as possible. Highly acute intersections can be problematic because of limitations on visibility, prolonged exposure of vehicles moving diagonally across the main traffic stream, and the difficulty in making a sharp turn, particularly for trucks and buses.
 - **Vertical alignment.** If possible, intersections should have gradients less than 3% in all directions. This is because vehicles approaching an intersection from any direction might need to stop, even when there's no stop sign or light in that direction, and stopping distances can be significantly increased for gradients larger than 3%.

- **The radius of curves at the corners of the intersection.** The rear wheels of a vehicle don't follow the same track as the front wheels, an inevitable consequence of the front-wheel steering systems our automobiles use. Because of this phenomenon, the pavement of a well-designed intersection is always extended inside of the traveled lane by an amount that will accommodate the type of vehicles that are expected to use the intersection.
- **Channelization.** **Channelization** is used to reduce conflicts by guiding traffic movements into well-defined paths, using either raised islands or pavement markings. Specifically, channelization can be used to control the flow of merging, diverging, and crossing traffic streams; segregate traffic movements that will receive different signals; provide storage lanes for turning vehicles; provide refuge for pedestrians; provide a place to mount traffic control devices; prevent prohibited turns; and restrict speed.
- **Adequate sight distance.** At intersections, drivers make decisions about whether to stop, start, accelerate, decelerate, turn, merge, diverge, or just continue at constant speed. Thus, it's incumbent on the designer to ensure that drivers approaching the intersection from all possible directions have adequate **sight distance** to make any relevant decision—and then to act on that decision without risk of collision.
- **Traffic control.** The three principal technologies for traffic control are signal lights, signs, and pavement markings. **Traffic control features** are designed to ensure the orderly, predictable, and safe movement of vehicles by formally assigning the right-of-way to various routes through the intersection. Signs and markings assign the right-of-way permanently; signals do it temporarily, on a rotating cycle. In all cases, the engineer's objective is to optimize the inevitable trade-off between delay and the probability of crashes for the conditions the intersection is expected to experience.

TERMS

at-grade intersection: In traffic engineering, an intersection at which all roads connect at the same level.

channelization: In traffic engineering, the use of raised islands or pavement markings to reduce conflicts by guiding traffic movements into well-defined paths.

grade-separated intersection: In traffic engineering, an intersection at which traffic streams cross at two or more different levels. Also called an **interchange**.

mean speed: In traffic engineering, the average speed of all vehicles passing a point on a highway within a specified period of time, measured in miles per hour.

sight distance: In traffic engineering, the distance a driver must be able to see in order to make a decision and then act on that decision without risk of collision.

traffic control feature: A signal light, traffic sign, or pavement marker designed to ensure the orderly, predictable, and safe movement of vehicles by formally assigning the right-of-way to various routes through the intersection.

traffic density: In traffic engineering, the number of vehicles traveling on a specific length of highway at a particular instant in time, measured in vehicles per mile.

traffic flow: In traffic engineering, the hourly rate at which vehicles pass a specific point on a highway, measured in vehicles per hour.

READINGS

Garber and Hoel, *Traffic and Highway Engineering*.

Hayes, *Infrastructure*, chapter 8.

QUESTIONS

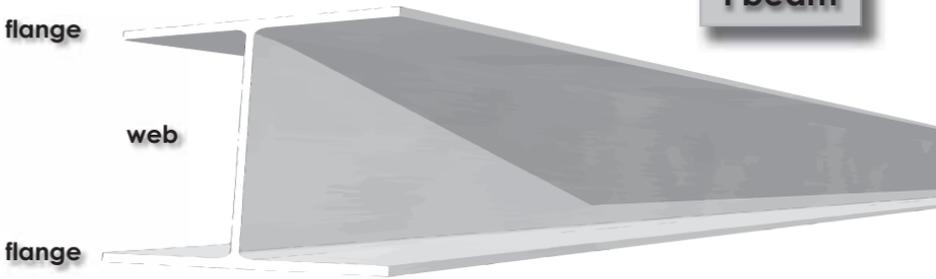
- 1 Why is it not always desirable to install additional traffic control measures at an intersection?
- 2 What are some considerations governing the design of exclusive left-turn lanes at intersections?

Everyday Bridges

Monumental structures like the Golden Gate Bridge represent extraordinary triumphs of human industry, ingenuity, and creativity. Yet, as iconic as they are, these great spans are unrepresentative of the bridges that have the greatest influence on our everyday lives. According to the Federal Highway Administration, there are more than 500,000 bridges in the United States. The vast majority of these are not graceful suspension bridges or towering arches but, rather, simple highway overpasses and modest spans across small streams. This lecture will focus on these seemingly mundane structures—bridges that can still inspire us, though perhaps in more subtle ways.

Multi-Girder Bridges

- ▶ Most of the bridges we encounter in our daily lives are simple multi-girder spans. The main structural elements in a multi-girder bridge are the girders. A girder is a main beam that supports other elements of the structural system. In your home, these “other elements” are the floor joists and subfloor. In a multi-girder bridge, they’re the components of the reinforced-concrete deck.
- ▶ A beam is a structural element that carries load in flexure, or bending. In this normal mode of bending, the beam develops compression on top and tension on the bottom. There is a horizontal plane, called the neutral axis, running through the middle of the beam, along which there is neither tension nor compression.
- ▶ Steel is an ideal material for girders—because it has equal strength in both tension and compression and because it can be formed into highly efficient I-shaped cross-sections. The “I” is an inherently efficient shape for carrying loads in flexure.



- ▶ The three components of an I-shaped beam are its two horizontal elements, called **flanges**, and the vertical element, called the **web**. When the beam bends, the flanges provide almost all of its flexural strength; the web is really just there to hold the flanges in place (and to resist several other types of loading). Theoretically, the farther the flanges are from the neutral axis, the stronger the beam will be.
- ▶ The steel girder that's commonly used in residential construction is called a **hot-rolled section**. It's manufactured by heating a single block of steel and then forming it into shape with huge hydraulically operated rollers. Some smaller highway bridges use girders made of hot-rolled sections, but most bridge girders are custom fabricated by welding individual steel plates together to form the flanges and web.
- ▶ These structural elements—called **plate girders**—are generally more efficient than hot-rolled sections, because they can be individually tailored to the requirements of a given structure. Plate girders can also be made much larger than even the largest hot-rolled beams; thus, plate-girder bridges are routinely built with spans exceeding 300 feet, while hot-rolled beams are only suitable for spans about one-third that length.
- ▶ But the quest to optimize a technology with respect to one performance criterion often creates problems with respect to other criteria. In the case of the plate girder, flexural strength and stiffness is enhanced by making

the cross-section taller and by using proportionately more material in the flanges. But as this cross-section gets taller and the web gets thinner, all kinds of new problems crop up, including **lateral-torsional buckling** and web buckling.

Bridge Failure

- ▶ Many older bridges use only two girders, which typically extend above the level of the roadway. But virtually all newer bridges use more than two girders. There are several reasons for this, but the most important one is that using a larger number of smaller girders provides improved safety through structural redundancy. If one girder of a two-girder bridge fails, the structure will almost certainly collapse. If one girder of an eight-girder bridge fails, the structure will almost certainly survive—saving lives and, ultimately, allowing for repair rather than replacement.
- ▶ Certainly, bridge engineers take every reasonable precaution to avoid failure, but the ugly truth is that a zero probability of failure is impossible to achieve. Sometimes, natural disasters load structures in ways that no engineer could anticipate, and sometimes the drivers of trucks and buses don't pay attention to overhead clearance restrictions.

A zero probability of failure is impossible to achieve.



- ▶ But the most important reason for structural redundancy is **fatigue**: the progressive accumulation of damage in metals subjected to repetitive loading. In a steel bridge girder, fatigue begins with a microscopic defect or crack in a web or flange—or, more likely, at a welded connection, where concentrations of stress tend to occur.
- ▶ If this portion of the girder is repetitively loaded in tension, each cycle of load extends the crack by a minute amount. Over time, as this process continues, the extension of the crack becomes progressively larger as the concentration of stress at the tip of the crack becomes higher. At some point—typically after a few hundred thousand load cycles—the crack can reach a critical length, at which point a sudden, catastrophic fracture of the entire girder occurs.
- ▶ Fatigue isn't a significant concern in steel-framed buildings, because buildings typically don't experience enough load cycles for fatigue cracks to approach their critical length. But major bridges are routinely crossed by thousands of heavy trucks per day—perhaps a million per year—and each truck produces a substantial load cycle that can contribute to fatigue damage. Thus, fatigue is an overriding concern in steel bridge design.
- ▶ Bridge engineers address this concern in three ways: by avoiding the specific types of welded connection details that are most prone to fatigue-related problems, through rigorous quality control in the fabrication and assembly of bridge components, and by providing structural redundancy. This approach is often called *belt-and-suspenders engineering*: Take every reasonable precaution to prevent failure, and then provide a backup system, just in case a failure happens anyway.

The Concrete Alternative

- ▶ The most fundamental characteristic of concrete as a structural material is that it's strong in compression but very weak in tension. And because beams experience comparable magnitudes of tension and compression, the only practical way to use concrete in flexure is to reinforce the portion of the beam that's in tension.

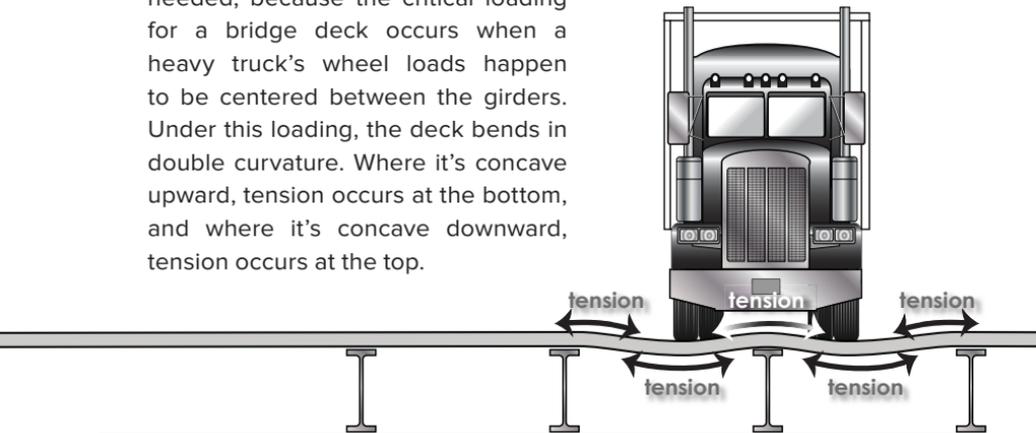
- ▶ In most structures, this reinforcement takes the form of steel reinforcing bars, which are positioned in the concrete forms before the concrete is poured. After the concrete has hardened, the steel and concrete are locked together into a single composite structural entity.
- ▶ Conventional reinforced concrete was used extensively for highway bridges in the early and mid-20th century, though today it's considered to be obsolete and has been largely replaced by a far superior technology.
- ▶ For steel to provide the necessary tension reinforcement in the bottom of a beam, it has to stretch. And the amount of stretch necessary to mobilize even a modest portion of the steel's strength is far beyond the threshold at which concrete cracks. Thus, the presence of moderate cracking in a reinforced-concrete beam tells us that the steel reinforcement is doing its job.
- ▶ But as normal as this might be, cracking causes two problems: It leads to significantly increased **deflection**, or sagging, of the beam; and cracks can expose the steel reinforcement to moisture, which leads to corrosion and, potentially, to a catastrophic loss of tensile strength.
- ▶ In building structures, where reinforced concrete is still used often today, these issues generally aren't problematic, because span lengths can be kept relatively short (to control deflections) and the building envelope can protect the beams from exposure to moisture. But in bridges, the need for longer spans and for constant exposure to the elements have effectively rendered reinforced concrete obsolete—and stimulated the development of a new technology called **prestressed concrete**.
- ▶ The concept of prestressed concrete is actually more than a century old, but the technology didn't really catch on for bridges until the 1950s. Since then, its use has grown steadily, even as improved materials and design methods have significantly improved its effectiveness and efficiency.
- ▶ For everyday bridges, there are two principal methods of fabricating prestressed concrete girders. Both occur in a controlled factory environment, not on the construction site. In both cases, the effect on

the concrete beam is essentially the same: The prestressing eliminates both the downward deflection and the cracking.

- ▶ In prestressed concrete, the effect of prestressing is to apply compressive stresses in the region of the beam that normally experiences tensile stress. In a material—like concrete—that’s strong in compression and very weak in tension, this offsetting of tension greatly improves structural performance.
- ▶ Prestressed concrete beams are I-shaped, meaning that they can achieve the same sort of structural efficiency as in steel girders. Yet, because of their more robust proportions, these girders are not susceptible to the lateral-torsional buckling or web buckling challenges that steel girders have. For these reasons, prestressed concrete has become highly competitive with steel for short- and medium-span bridges.

The Bridge Deck

- ▶ A few decades ago, a bridge deck would have been constructed by first erecting temporary wooden formwork between the girders, then adding two layers of steel reinforcing bars, and then pouring concrete over the entire assembly.
- ▶ Two layers of reinforcement are needed, because the critical loading for a bridge deck occurs when a heavy truck’s wheel loads happen to be centered between the girders. Under this loading, the deck bends in double curvature. Where it’s concave upward, tension occurs at the bottom, and where it’s concave downward, tension occurs at the top.



- ▶ Today, a bridge deck can be built at considerably lower cost by using corrugated steel decking instead of temporary formwork. The decking holds the wet concrete, just as formwork does, but it also provides tension reinforcement at the bottom of the deck—and thus replaces the lower layer of reinforcing bars.

TERMS

deflection: The bending deformation of a beam under transverse loading.

fatigue: The progressive accumulation of damage in metals subjected to repetitive loading.

flange: (1) One of two horizontal elements forming the top and bottom of an I-shaped structural element. (2) The raised edge on the inside of a steel railcar wheel.

hot-rolled section: A steel structural element manufactured by heating a block of steel and then forming it into shape with large hydraulically operated rollers.

lateral-torsional buckling: A structural failure mode in which the compression side of a beam (normally the top) buckles sideways, causing the beam to twist. Tall, narrow beam cross-sections are particularly vulnerable to lateral-torsional buckling.

plate girder: A girder fabricated by welding or riveting individual steel plates together, typically into an I-shaped cross-section.

prestressed concrete: A construction method in which prestretched steel reinforcing cables (called tendons) transfer compressive stress to a concrete structural element to control cracking and reduce deflections. The two methods of prestressing concrete are pretensioning and posttensioning.

web: The vertical element of an I-shaped structural shape or a railroad rail.

READINGS

Barker and Puckett, *Design of Highway Bridges*.

Hayes, *Infrastructure*, chapter 10.

QUESTIONS

- 1 Why are I-shaped steel girders used so commonly in highway bridges?
- 2 What is the structural advantage of continuous span girders, in comparison with simple spans? Why might the use of continuous spans be more challenging from a construction perspective?

Tunnel Engineering

While a grand suspension bridge is clearly an amazing engineering achievement, the tunnel carrying your subway line beneath a maze of city streets, or carrying your car safely beneath a mile-wide river, represents an engineering achievement that's entirely on par with a great bridge—in terms of both technological sophistication and grand ambition. In this lecture, you will explore the deep, dark world of tunnel engineering. You will learn about some of the major factors considered by the civil engineers who design tunnels, and you will be introduced to some of the highly specialized methods used to build them.

Soil Mechanics

- ▶ Different types of soils have astonishingly different mechanical properties. A compacted, well-graded gravel can be nearly as strong as concrete, but a wet, clay-rich soil is so slippery that it seems more like a lubricant than a structural material.
- ▶ Even within a particular soil category, there can be tremendous variability. All clays are not created equal. Furthermore, the structural behavior of soil often defies simplified theoretical idealizations that might work fine for manufactured materials, such as steel or concrete.
- ▶ For all these reasons, the engineering design of structures that interact with soil—foundations, retaining walls, and especially tunnels—is as much an art as it is a science. A tunnel design can never be based on theory alone but, rather, must be based on a comprehensive program of soil testing, augmented by extensive experience in tunnel engineering and construction methods.

- ▶ Soil testing is typically accomplished by drilling many boreholes into the earth and extracting samples from the depth at which the tunnel will be constructed, and then subjecting these samples to a battery of laboratory tests to determine such properties as soil type, density, cohesion, strength, and moisture content. The results of these tests can substantially influence a tunneling project.
- ▶ In many instances, the vertical and horizontal alignment of a tunnel are chosen based primarily on soil conditions. This is in sharp contrast with highways, which are typically located according to other criteria and then designed to accommodate whatever soil conditions are encountered along the route.
- ▶ For tunneling, one of the most important soil properties is the **standup time**, the length of time that an excavation's walls and ceiling will support themselves without structural augmentation. Rock and cohesive soils like clay typically have long standup times; sand and silt have quite low ones.
- ▶ This is important, because most tunnels require a **tunnel lining**, a structural inner shell that resists soil and water pressure while preserving the stability of the excavation. But the nature of the tunneling process is such that, as the tunnel is driven forward, there's always a time delay between excavation and construction of the lining. If the soil is able to stand on its own during this period, construction time and cost can be greatly reduced. If not, then elaborate measures to shield the tunneling machines and their operators from cave-ins are essential.
- ▶ Groundwater can have a major influence on standup time. In granular soils, a little bit of water can actually be helpful. But when an excessive quantity of water is present in the soil, the tunneling process must include provisions to remove it—to prevent instability of the soil. Typically, this is accomplished by continuous pumping, but some systems use a circulating refrigerant to freeze the soil in the immediate vicinity of the excavation.

- ▶ Regardless of standup time, all tunnels—except those driven through solid rock—require a structural tunnel lining. From the 19th through the mid-20th century, most linings were made of iron. But today, tunnel linings are nearly always concrete, applied in one of three forms to suit the prevailing soil conditions: cast-in-place concrete tunnel lining, segmental precast concrete lining, or sprayed concrete (also called **shotcrete**).

Types of Tunnels

- ▶ To a greater extent than any other form of construction, the design of a tunnel is inextricably interconnected with the methods and types of equipment that will be used during construction. For a bridge or a building, it's not unusual for an engineer to design the structure and then hand off the plans to a construction contractor, who is then expected to develop an appropriate construction plan. That simply can't happen with a tunnel, where design and construction must be thoroughly integrated.
- ▶ There are three principal types of tunnels, as defined by their construction methods: cut-and-cover tunnels, bored tunnels, and **immersed-tube tunnels**.
- ▶ The **cut-and-cover method** is generally used for tunnels positioned relatively close to the surface. In the most common approach—called the bottom-up method—a trench is dug to the required depth, typically using temporary supports to keep the walls of the excavation from collapsing inward. The tunnel lining is then built within the trench, the trench is backfilled, and the surface is restored.
- ▶ The great advantage of this method is its simplicity. Its disadvantage is that the ground surface above the tunnel is unusable for the duration of the project; thus, this technique is often problematic in congested urban areas.
- ▶ The alternative method is the top-down approach, in which construction begins by building the walls of the future excavation from ground level, typically by using a technique called concrete slurry-wall construction.

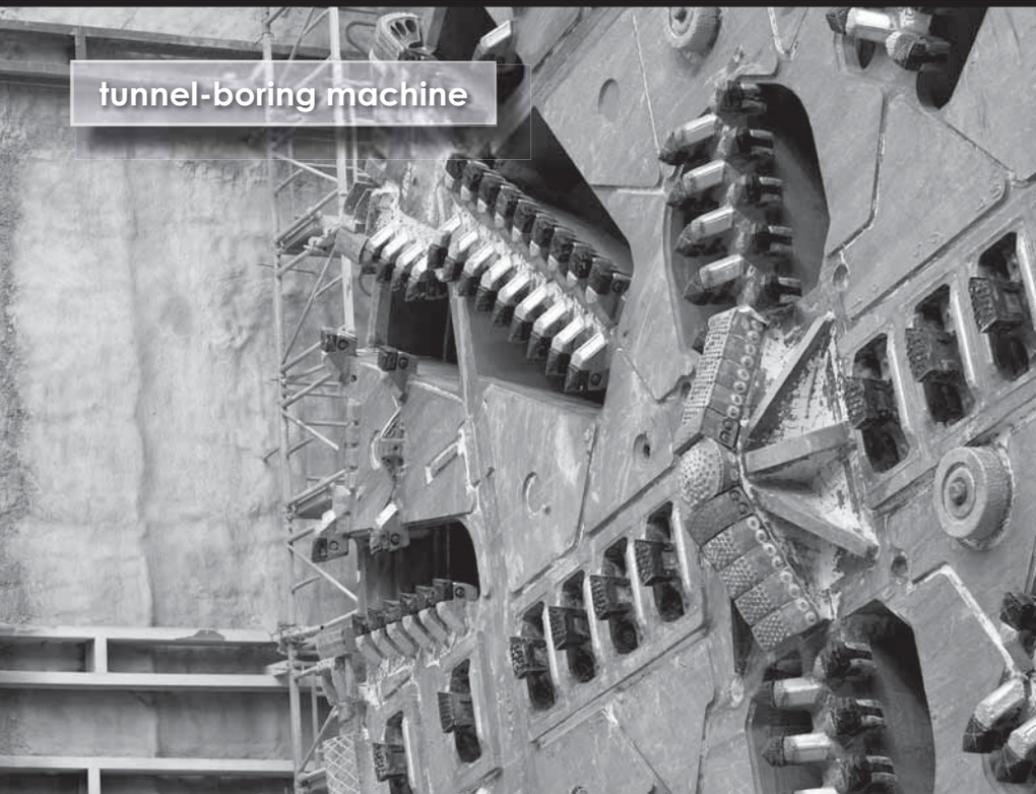
In this method, a narrow trench is dug where the future wall will be. During this process, the trench is kept filled with slurry, a heavy mixture of water and bentonite clay, which keeps the trench walls from collapsing inward. Once this trench is complete, cages of steel reinforcing bars are lowered into it, and then it's filled with concrete. The concrete displaces the slurry and eventually hardens to become a solid reinforced-concrete wall.

- ▶ The roof of the future excavation is then constructed at ground level, spanning from slurry wall to slurry wall. And apart from access openings, which must be left in the roof structure, the ground surface can now be restored and placed back into normal use. Beneath the roof, the main excavation now proceeds down to the appropriate level, and the remainder of the tunnel can be built without interfering with land use on the surface.
- ▶ The top-down method of cut-and-cover tunneling is considerably more challenging to manage than the bottom-up method, but it's often the only feasible alternative in congested urban areas, where land use is at such a premium.
- ▶ The second major category—the bored tunnel—is dug directly, from one or two access points on the surface, with little or no other disturbance to the ground surface above the excavation. For this reason, bored tunnels are particularly effective in congested urban areas and for tunneling beneath bodies of water.
- ▶ Several different technologies are used for constructing bored tunnels, but the most sophisticated is the tunnel-boring machine (TBM). Modern TBMs integrate the functions of excavation, protection from cave-ins, removal of excavated material, directional control, and installation of the tunnel lining all in one incredible machine.
- ▶ There are a numerous variations on the basic set of TBM functions, but regardless of configuration, these are immense machines with astonishing capabilities. In 1988, the eleven 25-foot-diameter TBMs used to dig the Eurostar rail tunnel under the English Channel were

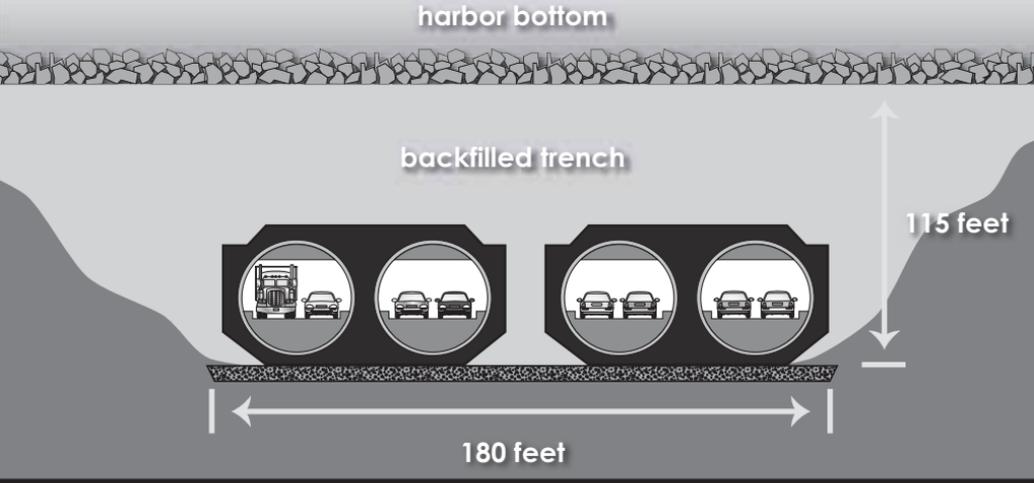
state-of-the-art systems. Today, TBMs that are more than 50 feet in diameter are routinely used to excavate tunnels for multilane highways. The up-front cost of a TBM is very high, but once in operation, it's a fast and cost-effective tunneling tool.

- ▶ Despite the availability of a wide array of high-tech tunneling machines, some modern bored tunnels are still constructed the old-fashioned way—by repeatedly drilling holes into the face of the excavation, packing these holes with explosives, setting off the charges, and clearing out the debris. This mode of tunneling is usually carried out beneath a protective shield, as well.
- ▶ The third major type of tunnel is the immersed tube, which provides an effective alternative to the bored tunnel for crossing a wide body of water. An immersed-tube tunnel is built of many tube segments, which

tunnel-boring machine



Fort McHenry Tunnel cross-section



are prefabricated on land and then floated into position, sunk to the bottom of the watercourse, and connected together. Tube segments are typically made of cast iron, steel, or precast concrete.

- ▶ In locations where the topography and riverbed conditions permit, immersed-tube tunnels are usually more cost effective than bored tunnels. They're both faster and safer to construct; they typically have better seismic resistance; and their feasibility is far less dependent on the character of the soil through which they pass. For a given riverbed profile, the depth of an immersed tube is always less than that of a tunnel bored beneath the riverbed; thus, the on-shore approaches to immersed-tube tunnels are typically shorter, as well.
- ▶ However, immersed tubes are more vulnerable to damage by waterborne traffic (due to anchor strikes, for example); they're more likely to have adverse environmental impact on the riverbed; and their successful construction and long-term serviceability are far more dependent on waterproofing and the integrity of the connections between segments.

- ▶ Regardless of category and construction method, the engineering challenges of tunnel design extend far beyond simply creating an underground thoroughfare. The design of long vehicular tunnels, in particular, requires extensive provisions for ventilation and fire protection.

TERMS

cut-and-cover method: A method of constructing aqueducts and tunnels. The tunnel lining is built at the bottom of a trench and then covered over with compacted soil.

immersed-tube tunnel: A type of tunnel built of multiple tube segments, which are prefabricated on land, floated into position, sunk to the bottom of the watercourse, and connected together.

shotcrete: Concrete that is sprayed onto a surface.

standup time: The length of time that the walls and ceiling of an excavation will support themselves without structural augmentation.

tunnel lining: A structural shell that covers the inner face of a tunnel, resists soil and water pressure, and preserves the stability of the tunnel excavation.

READINGS

Chapman and Metje, *Introduction to Tunnel Construction*.

Hayes, *Infrastructure*, chapter 10.

QUESTIONS

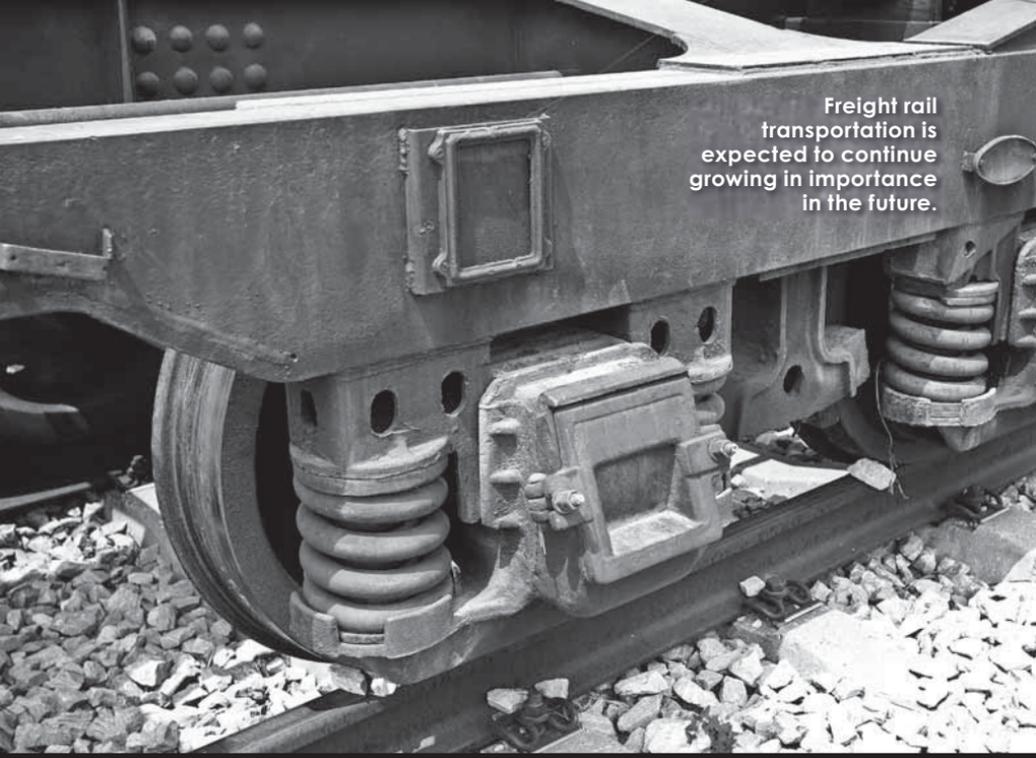
- 1** Under what circumstances would a tunnel be preferable to a bridge for crossing a body of water?
- 2** What methods are used to minimize the disruptions associated with constructing tunnels beneath major metropolitan areas?

The Railroad

We tend to think of the railroad as a vestige of the 19th century, but research shows that railroads currently carry more freight than any other mode of transportation in the United States. Thanks to the substantial growth in intermodal transportation and to growing recognition of trains' energy efficiency and low carbon emissions, freight rail transportation is expected to continue growing in importance in the future. In this lecture, you will examine this unique engineered system—one that will be an important part of our technological future, even though it's deeply rooted in the past.

Railroad Technology

- ▶ At the most fundamental level, railroad technology is characterized by steel wheels rolling on steel rails. In comparison with pneumatic tires on asphalt, this steel-on-steel interface allows for much heavier loads with much lower rolling resistance.
- ▶ Railroad rails serve both as structural supports and as guideways, allowing long chains of rolling stock to be pulled safely by a single source of tractive power. The cross-section of a rail is a highly optimized shape, called a T rail, consisting of three parts: the head, base, and web.
- ▶ The resemblance to an I-shaped beam is not coincidental. Under the weight of a train, a rail bends like a beam, so it makes sense that it's shaped like a beam. All rails in the United States use this characteristic shape, though sizes vary. Taller, heavier rails are used for railroad lines that carry the heaviest and fastest trains.
- ▶ The standard length of rail segments is 39 feet, primarily because the train cars used to carry them are 40 feet long. The traditional method of connecting rail segments together involves a bolted fishplate splice



Freight rail transportation is expected to continue growing in importance in the future.

that ties together the webs of two adjacent segments. A small gap is deliberately left between segments to allow for thermal expansion and contraction of the rail. When you hear that regular clickety-clack sound as a train passes by, you're hearing the sound of regularly spaced steel wheels passing over this gap.

- ▶ At many of these splices, a small copper wire extends from one side of the connection to the other. This wire provides electrical continuity across the splice—which is necessary because the rails are used as electrical conductors for most railroad signaling systems. When a train runs across a section of track, it completes a circuit, and current flows from one rail, through the steel wheels and axles, to the other rail—thus notifying the signaling system that a train is present on that particular stretch of track.

- ▶ This traditional connection system is still widely used today; however, on high-speed mainline track, it has largely been replaced by continuously welded rails. In this system, 37 standard 39-foot segments are welded end to end in the shop to create a single continuous 1440-foot-long rail, which is then loaded onto a string of rail cars for transportation to the location where the new rail is to be installed.
- ▶ While in transit, the rail bends elastically as the train goes around curves and then springs back on the straight stretches. These 1440-foot rails are then joined together end to end in the field to create a single continuous rail many miles long. The results are a smoother ride, less rolling resistance, and no clickety-clack sound.
- ▶ For a long time, continuously welded rails were thought to be structurally infeasible, because of their inability to accommodate thermal expansion. The expectation was that in extremely hot weather, restraint of thermal expansion would cause enough axial compression to **buckle** the rails. Indeed, substantial compression forces do develop in continuous rails, but they don't buckle because of the ties and **ballast**, which support the rails laterally—in essentially the same way that a steel bridge girder is laterally braced by **diaphragms** and the concrete deck.
- ▶ Steel railcar wheels have flanges on their inside edges. These flanges extend downward between the two rails, thus keeping the train from sliding off the tracks in either direction.

Railroad Networks

- ▶ The essential technology for combining individual sets of tracks into railroad networks is a mechanical device for switching trains from one line to another. It's often called a switch, but the proper term is a **turnout**. The key to the operation of a turnout is a pair of movable rails—called switch points—which have a standard T-rail cross-section at the far end but taper down to a point at the near end. The switch points move by bending sideways.

- ▶ Turnouts are used to create many characteristic features of railroad networks. There are three common ones.
 - A **siding** splits off of a main line, runs parallel to it for a considerable distance, and then rejoins it. Sidings allow a single rail line to carry two-way traffic, and they allow faster trains to pass slower ones when both are moving in the same direction on the same line.
 - A **lead**, often misidentified as a siding, is a branch line that terminates at a dead end, usually a factory or warehouse.
 - A wye is formed where three lines intersect, with each line connecting to the other two via turnouts. At a wye, a train on any of the three lines can make a U-turn.

- ▶ At locations where railroad lines intersect with vehicular roadways, special provisions are required to transmit the train safely across the intersection and to control automobile traffic. To convey automobiles across 6-inch-tall rails, the road surface must be built up to the level of the tops of the rails. However, the space between the rails can't be filled in completely, or there won't be a pathway for the flanges of the train wheels. Thus, the space between the tracks is typically filled with wooden or metal inserts, which leave a slot for each flange.

- ▶ Many different systems are used to control automobile traffic at grade-level crossings. These range from simple crossbuck signs to fully automated crossing gates with flashing lights. The associated systems for detection and control must be quite sophisticated, because they need to account for differing train speeds and lengths and even for the possibility that a train might stop or back up while crossing a roadway.

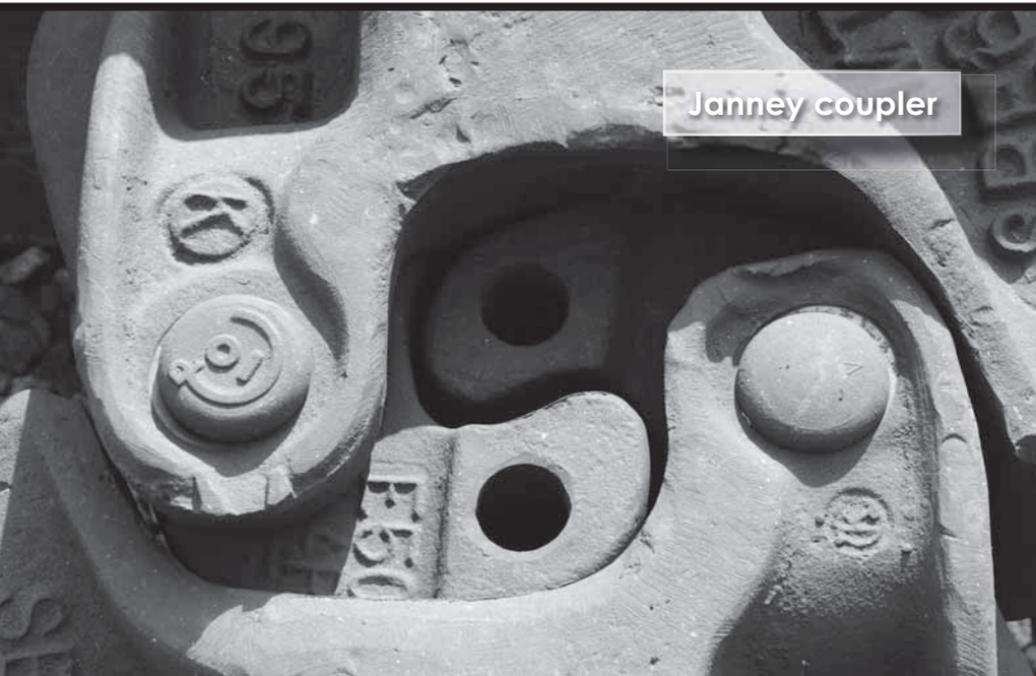
- ▶ From the macro perspective, freight railroad networks generally use a hub-and-spoke topology. The spokes are individual rail lines, which converge on regional hubs—fascinating facilities called **freight yards**.

Freight Trains

- ▶ The typical freight locomotive is powered by a huge 12- to 20-cylinder diesel engine, producing about 4000 horsepower. There are three major technological differences between a locomotive and a truck.
 - A locomotive needs no steering system.
 - The diesel engine in a locomotive doesn't actually drive the wheels. Rather, it drives a DC generator, which produces power for electric motors that turn the drive wheels.
 - A locomotive requires a far more robust braking system. Conventional automotive-type brakes, which use friction to slow the rotation of the wheels, are problematic, because of the tremendous heat buildup that would occur while stopping a train. Friction brakes are used on railcars, but most modern freight locomotives use regenerative braking—a system in which the electric motors stop driving the drive wheels and, instead, are driven by them. In effect, the motors become generators, converting shaft power from the drive wheels into electrical power, which is then dissipated through a network of large resistors. The resulting heat is dispersed by large fans that blow air across the resistors and out through the top of the locomotive.
- ▶ Behind the locomotive (or maybe two or three of them) is a seemingly endless variety of rolling stock, each type tailored for a specific purpose. Some of the more common ones include boxcars for general cargo hauling and refrigerated boxcars for produce, various types of flatcars for commodities ranging from lumber to truck trailers, container well cars for carrying shipping containers without wheels, tank cars for carrying liquids, gondola cars for bulk goods, open-top hopper cars for coal and stone, and closed-top hopper cars for goods that need to stay dry.
- ▶ The caboose—which provided sheltered accommodations for the crew, an office for the conductor, and an elevated, enclosed observation deck from which to keep an eye on the train—has nearly disappeared from the modern railroad. Today, this car has been replaced by a small

electronic box, mounted on the rear of the final railcar, that continuously monitors speed and braking system pressure and transmits these data by radio to the cab.

- ▶ Despite their seemingly infinite variety, nearly all railroad cars employ a common underlying mechanical design. The undercarriage is supported on two swiveling four-wheel assemblies called bogies. Each pair of steel wheels is fixed to a solid axle. The bogies are supported on coil springs, so the suspension system has some flexibility.
- ▶ At each end of the undercarriage is the device that connects adjacent cars together: the **Janney coupler**, which was invented by Eli Janney in 1868 and is essentially unchanged since then. When two Janney couplers come into contact with each other, they latch together and a locking **pin** falls into position automatically, thus eliminating the need for a railroad worker to occupy the very dangerous position between two cars during coupling. Once the couplers are latched, there's about a half inch of slack in the connection. This greatly enhances the locomotive's ability to accelerate when pulling a long train of cars.



Janney coupler

- ▶ The principal alternative to diesel power is the electric locomotive, which is quite popular in Europe but, in the United States, is used almost exclusively for urban mass transit systems and Amtrak's passenger lines in the Northeast Corridor. Compared with diesels, electric locomotives are more cost efficient, easier to maintain, and more environmentally friendly. They're also more suitable for high-speed operations—and, thus, are particularly useful for passenger service. However, the extensive additional infrastructure required for electric railroads entails significantly higher infrastructure costs.

TERMS

ballast: A layer of gravel used to provide support for railroad ties.

buckling: A failure mode in which a member subjected to compression becomes unstable and bends laterally. Buckling failure is sudden and usually catastrophic.

diaphragm: (1) A thin disk that vibrates when receiving or producing sound waves, as in a microphone or speaker. (2) A cross-frame used to connect parallel beams or girders together in a structural system.

freight yard: A railroad hub at which incoming trains are broken apart and reorganized into outgoing trains based on the destination of their cargo.

Janney coupler: The mechanism used to connect two railcars together.

lead: A branch railroad line that terminates at a dead end.

pin: A structural support that permits rotation but restrains both horizontal and vertical movement.

siding: A branch railroad line that splits off of a main line, runs parallel to it for a distance, and then rejoins it.

turnout: A railroad switch at which one rail line branches off from another.

READINGS

Hayes, *Infrastructure*, chapter 9.

U.S. Department of Transportation, *Freight in America*.

QUESTIONS

- 1** Why are 150-year-old technologies, such as the Janney coupler and the Westinghouse braking system, still used on modern freight railcars? What broader conclusions might we draw about technological development based on this phenomenon?
- 2** Railroads have used a hub-and-spoke topology for more than a century. More recently, commercial airlines have adopted essentially the same organizational structure. Why is the hub-and-spoke organization economically advantageous in both cases?

Solid Waste Disposal and Recycling

In the United States, we generate about 4.5 pounds of solid waste per person per day—nearly a ton per person per year. Aggregated across the entire population, the numbers are staggering. For example, we use 80 billion aluminum cans per year, 22 billion plastic bottles per year, and paper and wood products amounting to 2 billion trees per year. In this lecture, you will examine the three principal methods of dealing with all of this waste: disposal in a landfill, incineration, and recycling.

Landfills

- ▶ A modern **sanitary landfill** is a technological system designed by environmental engineers to return solid waste to the earth in a way that maximizes the use of available land and minimizes harm to the environment.
- ▶ When organic material is placed in a landfill, it begins to decompose through the action of bacteria and other microorganisms. When rainwater percolates down through this material, the moisture promotes decomposition, and in the process, the water also becomes contaminated with dissolved organic matter, heavy metals, and a variety of other substances.
- ▶ The resulting toxic, acidic liquid is called **leachate**, and the most important objective of a sanitary landfill design is to contain, collect, and remove the leachate to prevent contamination of the local groundwater, streams, and rivers.
- ▶ Decomposition of organic material also generates a by-product known as **landfill gas**, a mixture of methane, carbon dioxide, and small amounts of nitrogen, oxygen, and other gases. Landfill gas is explosive, and its two principal components—methane and CO_2 —are greenhouse gases; thus, a secondary objective of landfill design is to detect, capture, and dispose of dangerous accumulations of landfill gas.

- ▶ Construction of a typical modern landfill begins with excavation of a broad, flat-bottomed pit roughly 25 feet deep. The excavated soil is stockpiled so that it can be used for cover later. Next, the bottom and sides of the pit are sealed—first with a layer of compacted clay, and then with a waterproof **geo-membrane**. Clay is used for its impermeability. A geo-membrane is a strong, flexible, puncture-resistant, thin plastic sheet that also has very low permeability. The clay liner and geo-membrane serve as a belt-and-suspenders liner to prevent leachate from entering the soil beneath the landfill.
- ▶ A thick layer of gravel is placed over the membrane, both to protect it and to allow for the free flow of leachate. Embedded within this layer is the leachate collection system, a network of perforated plastic pipes that capture any leachate entering the gravel bed from above and channel it down to low points called sumps. Within each sump is a pump that transports any accumulated leachate out of the landfill for disposal.
- ▶ This leachate collection system is essential, because no geo-membrane is perfectly impermeable. Without a well-functioning collection system, leachate would accumulate on the membrane and would eventually seep through it and contaminate the surrounding soil.
- ▶ Above the gravel layer is a durable synthetic fabric called a **geotextile**, covered by a protective layer of sand or other soil. Unlike a geo-membrane, a geotextile is intended to be permeable. It serves as a filter, allowing the leachate to pass through but preventing soil and other solid material from entering the gravel bed and clogging up the leachate collection system.
- ▶ With this uppermost layer of soil in place, the facility is ready for operation. In the typical landfill, garbage trucks deposit their loads at the base of a sloped embankment called the working face. **Bulldozers** and rollers are then used to distribute and compact this trash along the slope.

bulldozer



- ▶ Each day's deposit of trash is confined to a rectangular area called a cell. The size of a cell can vary significantly, depending on the amount of trash produced by the local municipality. In general, the goal is to keep the cell's footprint as small as possible, for more efficient management of available landfill space.
- ▶ By the end of each day, the compacted trash in the cell will be 4 to 8 feet thick, and then it'll be completely covered with 6 to 12 inches of soil and compacted once again. This application of soil—called daily cover—keeps the trash contained, reduces water infiltration, controls odors, and discourages insects and scavengers from taking up residence. The next day, this process starts all over again with the creation of a new cell.
- ▶ Once daily cells have been stacked all the way up to the original grade level, this section of the landfill is capped. The cap typically consists of a layer of compacted clay, then a geo-membrane sealer, a drainage layer of gravel or sand, and a protective layer of soil. Topsoil is added to the top of the cap, and then vegetation is planted to stabilize the soil and prevent erosion.

- ▶ The cap is normally crowned so that as much storm water as possible will run off rather than percolating down into the landfill. The overall intent of the cap is to minimize water infiltration and thus to minimize the production of leachate.
- ▶ With the cap in place, the conditions are ripe for the dangerous buildup of methane underground, so a gas-collection system is typically installed at this time. Indeed, in the United States, the Clean Air Act Amendments of 1996 require the systematic collection and control of landfill gas.
- ▶ Until relatively recently, this requirement was usually met by piping the gas to a flare, where it was simply burned off. But today, an increasing number of landfills are incorporating recovery systems that put landfill gas to more productive use—by burning the gas in a nearby industrial boiler to produce hot water, using it to generate electricity by powering an on-site gas turbine or steam turbine that drives a generator, or processing the gas for sale to the local gas company.
- ▶ When a landfill is completely filled, it's fully capped and closed. And while the surface of the land might then be converted to other uses, what's happening below the surface—the continued production of leachate and landfill gas—must typically be monitored for at least 30 years afterward. The reason is that well-designed landfills limit decomposition rather than promoting it, by preventing water and air from coming into contact with the buried trash, to the greatest extent possible.

Incineration

- ▶ One of the two principal alternatives to the landfill is incineration. In many ways, the concept of incineration seems ideal. Burning waste reduces its weight by 80% and its volume by 95%, and the resulting heat can be used to generate electrical power. The by-product of incineration is a small quantity of inert ash that takes up a tiny fraction of the landfill space that would have been occupied by the original material. Incineration largely eliminates the problem of methane emissions from landfills. And,

incinerator



paradoxically, the use of incineration has been found to improve rates of recycling—primarily because metals can be separated from other materials more easily by burning than by mechanical disassembly.

- ▶ However, despite these desirable features, less than 15% of municipal solid waste in the United States is incinerated today, and this percentage is on the decline. There are three main reasons why.
 - The emissions caused by incineration are highly toxic.
 - Incineration also produces substantial carbon dioxide emissions.
 - From the perspective of power production, municipal solid waste is a very poor-quality fuel.

- ▶ These challenges aren't insurmountable. Japan and several European countries have been quite successful in implementing large-scale environmentally responsible trash-to-power projects. In the United States, however, this approach to solid waste disposal is evidently not a growth industry.

Recycling

- ▶ The third approach is recycling: the process of salvaging waste and transforming it back into usable materials. Recyclable materials include metals, glass, plastic, paper, textiles, and electronics.
- ▶ Recycling bins at curbside have become a fact of life in modern society. In the United States today, roughly 30% of municipal solid waste is recycled—more than triple the percentage from 1980. However, the viability and effectiveness of recycling remains highly dependent on the specific materials being recycled.
- ▶ Recycling aluminum is amazingly efficient. The process requires only about 5% of the energy consumed in producing aluminum from raw bauxite ore, so there's a strong economic incentive for manufacturers to use recycled material. And there's no limit to the number of times aluminum can be melted down and reused.
- ▶ Recycling steel isn't quite as efficient. Cooking up a batch of steel from scrap takes about 40% as much energy as producing it from iron ore. But that's still a substantial saving in an energy-intensive process like steel making. As a result, in the United States today, more than 95% of structural steel is recycled, and several major producers now manufacture 100% of their steel from scrap.
- ▶ Glass is recycled by simply crushing and remelting it, a relatively efficient process that consumes only about 70% of the energy required to make glass from scratch. But because glass retains its color after recycling, manufacturing bottles from recycled glass requires that the glass be strictly segregated by color: brown, green, or clear. This need for sorting imposes an additional cost on the recycling process, and it can also cause some supply-and-demand challenges. In recent years, this limitation has been eased by the development of new recycled-glass applications that don't require segregation by color.

- ▶ Of all the major recycled products, plastic is most problematic—in part because there are so many different types of plastics, but especially because very few of them can be remelted back to their original pure polymer form.
- ▶ Recyclable plastic is generally marked with a resin identification code—the familiar number-inside-a-triangle logo—that identifies the type of polymer used in its manufacture. The standard resin identification codes are numbered from 1 to 7, though in many U.S. municipalities, only codes 1 and 2 are collected in curbside recycling programs. The result is a lot of public confusion about what can and can't be recycled. For these reasons, less than 10% of our discarded plastics are recycled.

TERMS

bulldozer: A piece of construction equipment that is used for moving soil over short distances.

geo-membrane: A flexible, puncture-resistant, low-permeability plastic sheet that is used in the liner of a sanitary landfill.

geotextile: A durable, permeable synthetic fabric that is used as a filter in a sanitary landfill.

landfill gas: A mixture of methane, carbon dioxide, and small amounts of other gases formed by the decomposition of organic material in a sanitary landfill.

leachate: A toxic, acidic liquid that accumulates within a sanitary landfill as a result of rainwater percolating down through the solid waste.

sanitary landfill: A solid waste disposal facility designed to return the waste to the Earth in a way that maximizes the use of available land and minimizes harm to the environment.

READINGS

Hayes, *Infrastructure*, chapter 13.

Nazaroff and Alvarez-Cohen, *Environmental Engineering Science*.

QUESTIONS

- 1 What are the environmental hazards associated with the operation of a sanitary landfill? How does the design of a landfill mitigate these risks?
- 2 How could the manufacturers of household products facilitate and promote improved rates of recycling?

The Future: Engineering for Sustainability

In previous lectures, you've explored various approaches to conserving energy, reducing pollution, and reducing solid waste disposal through recycling. However, effective as these measures might be, they haven't yet had the large-scale impact we need, largely because each addresses one particular aspect of the problem in isolation. What's needed is a more holistic approach. And, indeed, just such an approach is currently taking hold: design for sustainability, or sustainable engineering. As you will learn in this lecture, sustainable engineering is engineering that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Sustainable Engineering

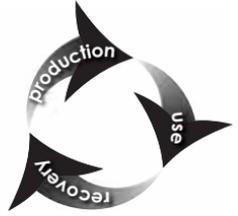
- ▶ The most fundamental premise of **sustainable engineering** is that we must look holistically at the entire life cycle of the products we develop. The traditional, non-sustainable approach to product development is a simple linear process that starts with extraction of raw materials and ends with disposal of the product, when it's reached the end of its useful life.

traditional product development



perfectly sustainable product development

- ▶ In the perfectly-sustainable-but-unachievable alternative, production, use, and recovery occur in an infinite cycle. The pragmatic middle ground is a reasonably sustainable approach in which we seek to repeat the production-use-recovery cycle as many times as possible but acknowledge that some external sourcing and disposal of material resources will usually be required at the beginning and end of a product life cycle.



reasonably sustainable product development

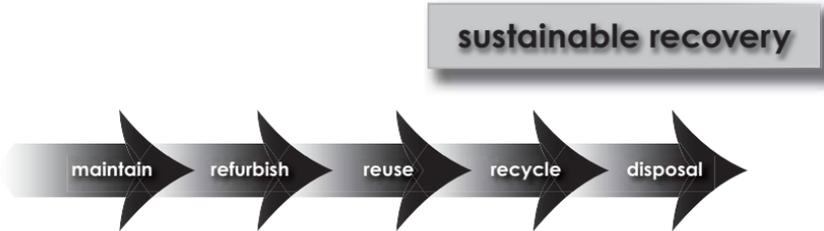
- ▶ The most important difference between the traditional and sustainable models of product development is the recovery phase. But this doesn't mean that sustainability is only considered during the recovery phase. Indeed, the most important aspect of the sustainable model is that sustainability must guide the implementation of all five phases. To illustrate this point, let's consider this model in the context of some everyday technologies you've encountered throughout this course.
- ▶ In residential construction, for example, the sustainable sourcing of materials might include the use of engineered lumber, such as oriented strand board and plastic lumber, rather than conventional sawed lumber, because engineered products use wood fiber far more efficiently.



- ▶ It might include the use of roof trusses, rather than rafters, because trusses are more structurally efficient and thus use significantly less lumber.
- ▶ It might include the use of cellulose insulation, which is manufactured from recycled newsprint and has an R-value comparable to fiberglass batting.
- ▶ It might include the use of metal roofing, rather than asphalt shingles, because metal roofing lasts longer and is more easily recycled. In the United States alone, 11 million tons of waste asphalt shingles are dumped into landfills every year, while nearly 100% of waste steel goes back into the furnace to manufacture new steel products.
- ▶ Sustainable sourcing also entails using locally produced materials wherever possible, because shipping materials halfway around the globe consumes substantially more energy and, in particular, more fossil fuels.
- ▶ The concept of sustainable production is best represented by the growing number of companies that are building “smart factories”—facilities employing such technologies as on-site renewable power generation, low-energy lighting, rainwater harvesting, water recycling, and on-site wastewater treatment—with the resulting methane gas captured and used as fuel. These factories are able to manufacture useful products with drastic reductions in energy consumption and dramatically less environmental impact.
- ▶ Sustainable production also can be enhanced through advanced engineering processes like 3-D computer modeling and simulation, which significantly reduce the number of physical prototypes that need to be fabricated during the design and testing of new products.
- ▶ Sustainable use is exemplified by all of the residential energy efficiency measures you learned about in the lectures on this subject, including the use of enhanced insulation and air-sealing methods, energy-efficient heating and air-conditioning equipment, and local renewable power generation—all of which reduce the consumption of energy during the entire useful life of a house.

Sustainable Recovery

- ▶ You might think of sustainable recovery as being synonymous with recycling, but it's actually much broader. There is a hierarchy of sustainable recovery options that might be taken at the end of a product's useful life: maintain, refurbish, reuse, recycle, disposal.



- ▶ The first priority in sustainable recovery is rigorous maintenance to extend the life of the product. If you change your car's engine oil often, you'll prolong its useful life and, thus, delay the significantly greater consumption of resources associated with disposal and replacement of the engine or the entire car. Eventually, however, a major component like the transmission will fail, and you might choose to have it refurbished or replace it with a previously refurbished transmission, which you'll reuse.
- ▶ Both of these options consume considerably less energy and fewer resources than buying a newly manufactured transmission and, thus, are preferable from a sustainability perspective. If you must replace a component that can't be refurbished, then it should be recycled. And only in cases where recycling isn't possible should the component, or the system as a whole, be hauled off to a landfill or incinerator for disposal, in an environmentally responsible way.
- ▶ This five-phase model of sustainable product development is filled with good ideas, but how can they be implemented in a comprehensive way? The answer is that sustainable sourcing, production, use, recovery, and disposal must be designed into the product from the outset. Thus,

the principal responsibility for sustainability lies with the engineer or architect who has principal responsibility for the design.

- ▶ Your new house won't be oriented to maximize solar gain unless the designer applies passive solar design principles from the start. Your house won't be built with structural insulated panels unless it's specified by the designer. And recycling will never be optimized until products and their packaging are purposefully designed with recycling in mind.

Applying Sustainable Design Principles

- ▶ If designers are principally responsible for sustainability, how do we ensure that they apply sustainable design principles in their work? There are several feasible approaches.
- ▶ One is government action—either legal mandates or incentive programs—and this approach can indeed produce results. For example, in 1991, Germany passed a law that assigned responsibility for the entire life cycle of all packaging to manufacturers. The appeal of this system is that it provides a strong economic incentive for manufacturers to avoid overpackaging and to design packaging that lends itself to efficient recycling. As a result, recycling rates in Germany are typically above 60%, about twice that of the United States.
- ▶ The success of this particular initiative notwithstanding, today the most important advances in sustainability are happening without government intervention. There are two reasons for this encouraging trend.
 - Many aspects of sustainability are good for business. It's not unusual for "smart factories" to use half as much power and water as conventional factories. That sort of reduction is just as beneficial for the bottom line as it is for the environment. Moreover, consumers are demonstrating, in increasing numbers, that they're willing to support companies that operate sustainably and to pay for sustainable products.

- Within the past decade, the engineering community has embraced sustainability as a professional responsibility and as a major focus area for the future. At the most fundamental level, this is not really a change of direction for the engineering profession; the ethical focus of engineering has always been on serving humankind. But today, engineers have begun to recognize that their obligation to serve extends to future generations as well as their own.
- ▶ The professional community's embrace of sustainability has already resulted in the inclusion of new energy-efficiency provisions in building codes, substantial research and development in sustainable design, inclusion of sustainability provisions in professional codes of ethics, and adoption of rigorous sustainability certification programs—for individual architects, engineers, and builders; for the materials they use; and for the products of their work.
- ▶ One such certification program is LEED—which stands for Leadership in Energy and Environmental Design—a program initiated by the U.S. Green Building Council in 2000. LEED provides voluntary certification of commercial buildings, schools, health-care facilities, neighborhood-development projects, and private residences.
- ▶ In the LEED certification process, projects are evaluated according to a broad range of sustainability criteria organized into credit categories. Points are awarded in each category, and the point total is used as the basis for assigning one of four possible certification levels (from highest to lowest): LEED Platinum, LEED Gold, LEED Silver, and LEED Certified.
- ▶ The LEED credit categories for private homes reflect the holistic nature of the rating system.
 - The Integrative Process category gives credit for the use of an integrated project team to manage both design and construction.
 - The Location and Transportation category rewards avoidance of sensitive land and access to energy-efficient transportation.

- The Sustainable Sites category recognizes low-impact storm-water management practices.
 - The Energy and Atmosphere category allocates points to such factors as building orientation, insulation, windows, control of air infiltration, hot-water distribution, lighting, and appliances.
 - The Materials and Resources category rates the use of environmentally friendly construction materials and waste-management practices.
 - There are also categories for Indoor Environmental Quality, Water Efficiency, Innovation, and Regional Priority.
- ▶ Despite the entirely voluntary nature of this program, more than 50,000 projects have been LEED certified since 2000, and the rate of participation continues to grow. More importantly, LEED certification has become a badge of honor among building owners, architects, and engineers—a very exciting development that can only further the cause of sustainable design.

TERM

sustainable engineering: Engineering that meets the needs of the present without compromising the ability of future generations to meet their own needs.

READING

Johnson and Gibson, *Sustainability in Engineering Design*.

QUESTIONS

- 1 Why is the use of locally produced materials considered to be more sustainable than the use of less expensive materials obtained from more distant sources?
- 2 How can computer modeling and simulation make industrial production more sustainable?

Glossary

activated sludge: A process used in the secondary treatment of sewage. Wastewater is combined with carefully managed populations of bacteria, protozoa, worms, and microscopic animals that consume the organic compounds in the water and thus reduce its biochemical oxygen demand (BOD).

adjacency: An aspect of an architectural design dealing with the proximity of rooms and other functional spaces to each other.

advanced framing: An adaptation of the traditional platform-framing method for residential construction. Advanced framing provides better energy efficiency, better sustainability, and lower cost.

aeration: The introduction of oxygen into water, for the purpose of reducing anoxia.

affordance: In user-centered design, a message conveyed by the physical configuration or placement of an object about how people can interact with it.

alkane: A chemical compound consisting of a chain of carbon and hydrogen atoms with the general chemical formula C_nH_{2n+2} , where n is the number of carbon atoms. Alkanes are hydrocarbons that constitute a major component of unrefined crude oil.

alignment: In highway design, the path a highway takes across the ground. A road alignment includes both vertical and horizontal components.

alternating current (AC): A current that varies continuously in a recurring sinusoidal cycle, typically because it is produced by a rotating generator.

altitude: In orbital mechanics, the distance from the surface of a planet to an orbit. The radius of an orbit is equal to the altitude plus the radius of the planet.

amplifier: In telecommunications, a device that uses externally supplied energy to boost the power of an input signal.

amplitude: The maximum height (or magnitude) of a waveform.

amplitude modulation (AM): A form of modulation in which the amplitude of the carrier signal is modified to match the amplitude of the voice signal.

anaerobic: Occurring in the absence of oxygen.

anaerobic digestion: A process of bacterial decomposition in the absence of oxygen that is used for the treatment of sludge at a sewage treatment facility.

analog: In telecommunications, a continuously varying signal that is analogous to the sound waves it represents.

annular gear: A ring-shaped spur gear with teeth oriented inward, typically used as a component of a planetary gearset.

anoxia: The depletion of dissolved oxygen near the bottom of a body of water.

antenna: An electrical conductor that generates electromagnetic waves for wireless transmission of information or that receives such transmissions.

antilock braking system (ABS): An automotive braking system that enhances traction and control by using electronic sensors to detect when a wheel is about to lock up and then releasing and reapplying the brakes in short pulses, many times per second.

apogee: The highest point in an elliptical orbit.

aqueduct: A conduit used to transport water from its source to its point of use.

aquifer: A porous stratum of soil or rock in which groundwater collects.

arch: A structural element that carries load primarily in compression and must have its outer ends laterally restrained in order to carry load successfully.

arch action: A phenomenon that occurs in soil when loss of support in one underground location (e.g., an excavation) causes a redistribution of load to the undisturbed adjacent soil.

arch dam: A dam that resists hydrostatic pressure through the action of an arch that transmits load in compression to the walls of the valley in which it is constructed.

arterial: A road that provides long-distance mobility, facilitating movement from one region or city to another.

associated gas: Natural gas that is found within, and extracted from, underground petroleum deposits.

at-grade intersection: In traffic engineering, an intersection at which all roads connect at the same level.

attenuation: In telecommunications, the tendency of a transmitted signal to become weaker with increasing distance traveled.

attitude: The orientation of a satellite, spacecraft, or other orbiting body in three-dimensional space.

balanced earthwork: In highway design, the condition in which the total amount of soil removed from the cut sections is equal to the total amount of soil placed into the fill sections.

ballast: A layer of gravel used to provide support for railroad ties.

balloon frame: The original light wood frame structural system, developed by George Washington Snow in the 1830s. By exploiting the availability of standardized lightweight lumber and nails, the balloon frame revolutionized residential construction in North America.

bandwidth: A range of frequencies.

base station: In a cellular network, a facility that contains the transmitters, receivers, and antennas required for communication with mobile devices located within the associated cell.

base station controller: A device that connects multiple cellular base stations to their associated mobile switching centers.

beam: A structural element that carries load primarily in flexure or bending.

bearing wall construction: A structural system in which the principal vertical load-carrying elements are the exterior walls of the building.

Bernoulli's principle: When the speed of a moving fluid increases, its pressure decreases, and vice versa.

bevel gear: A gear with a beveled edge, which allows the transmission of torque between two shafts oriented at any angle between 0° and 180° with respect to each other.

bias-ply tires: A vehicle tire with its internal reinforcing plies oriented in an alternating diagonal pattern.

bimetallic strip: A device for measuring changes in temperature based on the thermal deformation of two metals bonded together.

biochemical oxygen demand (BOD): The depletion of dissolved oxygen in water as aquatic bacteria and other microorganisms consume organic compounds as food. Wastewater has a high BOD, which must be reduced through secondary treatment.

bioreactor: A vessel in which the activated sludge process is implemented for secondary sewage treatment.

biomass: A form of renewable energy obtained from plant material or animal waste. Biomass is converted into energy by burning wood, manufacturing

ethanol-based fuel from plants, capturing methane gas from decomposing organic material, and a variety of other means.

bit: The basic unit of information in digital communications. A bit can have only two possible values: 1 or 0.

bit rate: The rate of digital data transmission, measured in bits per second.

blower: A centrifugal fan.

boil: To change from the liquid phase to the vapor phase.

boiling water reactor (BWR): A type of nuclear power generation facility in which the reactor coolant water is allowed to boil, and the resulting steam is circulated through the turbines to generate power.

brake band: In an automatic transmission, a steel strap that, when pulled tight by hydraulic actuators, locks certain components of a planetary gearset.

brake fade: The tendency of automotive brakes to lose effectiveness due to the buildup of heat.

buckling: A failure mode in which a member subjected to compression becomes unstable and bends laterally. Buckling failure is sudden and usually catastrophic.

building code: A set of rules specifying minimum standards for construction. Building codes are normally enacted through legislation.

building envelope: An assemblage of building components that protect interior spaces from the elements and control interior temperature and humidity, while also allowing for access, egress, and natural illumination.

building science: The scientific study of physical phenomena affecting buildings.

bulldozer: A piece of construction equipment that is used for moving soil over short distances.

bursty data: Data transmitted through a network in short spurts, separated by longer periods of inactivity.

bus: (1) In electrical power distribution, a set of electrical conductors used to route power through a substation. (2) In a communications satellite, the equipment responsible for transporting the mission payload into orbit and providing electrical power, attitude control, temperature control, and orbital adjustments.

bushing: In electrical power transmission and distribution, an insulated fitting that allows a high-voltage conductor to pass through a grounded metal case without causing a flashover.

capacitor: A device used to store electric charge. A capacitor typically consists of two metal plates separated by a dielectric material.

capillary action: The tendency of a liquid to be drawn into a fine-grained or finely divided solid.

carbon sequestration: A process—currently under development—by which carbon dioxide is captured from the furnace exhaust of a coal-fired power plant and either stored in geologic formations deep underground or reacted chemically with metal oxides to produce stable, solid materials called carbonates. Also called **carbon capture**.

carrier: In telecommunications, an electromagnetic signal in which information is encoded for transmission.

cell phone: A radio transmitter-receiver used in cellular communication.

cellular communication: A wireless communication system that uses analog or digital encoding of a radio carrier signal.

cellular reuse pattern: In a cellular communication system, the number of adjacent cells in a module that cannot use the same frequencies.

channel: In telecommunications, the pathway through which a stream of information is transmitted.

channelization: In traffic engineering, the use of raised islands or pavement markings to reduce conflicts by guiding traffic movements into well-defined paths.

chemical energy: A form of energy associated with the bonds between the atoms that constitute molecules.

circuit: (1) An electrical conductor formed into a closed loop, thus allowing current to flow in response to a voltage. (2) A telecommunications channel that is transmitted on a physical medium (e.g., copper wire, coaxial cable, or optical fiber).

circuit breaker: A switch that interrupts electric current in a conductor, either for maintenance or to prevent damage to the system in the event of a short circuit or other abnormal event.

circuit-switched network: A communications network in which information is transmitted through a dedicated communications channel from one terminal through one or more intermediate nodes to another terminal. The connection must be fully established, end to end, before the transmission can begin, and then it is released after the transmission is complete.

cladding: The outer layer of a building envelope, typically consisting of brick, stone, stucco, or siding.

clarification: In water treatment, the process of removing suspended particulate matter from raw water.

clay: An extremely fine-grained soil formed from the weathering of silicate-bearing rocks. Clay is highly cohesive—capable of holding its shape without crumbling—and impervious to water.

clock bias: In the global positioning system, the difference between satellite time and receiver time. Clock bias is accounted for in the navigation equation.

clutch: A device that is used to connect and disconnect a driving shaft from a driven shaft while one or both shafts are turning.

coagulant: A chemical substance used for clarification in water treatment. The coagulant causes suspended particles to cling together, resulting in clumps of impurities—called flocs—sinking to the bottom of the container.

coal: A black or brownish sedimentary rock, composed primarily of carbon, mixed with varying amounts of impurities—primarily hydrogen, sulfur, oxygen, and nitrogen.

coaxial cable: A high-capacity telecommunications cable developed as a replacement for twisted copper wires in the interexchange trunks of the public switched telephone network (PSTN).

code-division multiple access: A system for wireless communication in which all mobile devices within a given cell communicate across the full frequency spectrum at the same time by modulating each signal according to a unique, randomly generated code provided by the cellular base station. Also called **spread-spectrum multiple access**.

coefficient of static friction: The ratio between the static friction force and the associated normal force acting on a body at rest.

coefficient of thermal expansion: A material property that indicates the propensity of the material to undergo thermal deformation.

collector: A road that conveys traffic between the local roads and arterials.

column: A vertically oriented structural element that carries load primarily in compression.

combustion turbine: A turbine engine that is propelled directly by the combustion of natural gas.

compression: An internal force or stress that causes shortening of a structural element.

compression ratio: In an automobile engine, the ratio of the cylinder volumes, V_2 to V_1 , where V_1 is the volume at top dead center and V_2 is the volume at bottom dead center.

compressor: A mechanical device that increases the pressure of a fluid while reducing its volume.

concrete: A mixture of Portland cement, sand, and gravel that hardens into a rocklike mass when mixed with water.

condense: To change from the vapor phase to the liquid phase.

condenser: A device that changes vapor into liquid by transferring heat from the fluid.

conduction: Heat transfer through a substance or through physical contact between substances.

conductor: A metal wire or cable that provides a path for the flow of electric current.

connecting rod: In an automobile engine, a link that connects a piston to the crankshaft.

constraint: In user-centered design, a physical limitation that communicates how a device can or cannot be used.

contact patch: The interface between a vehicle tire and the surface on which it rests.

containment building: A massive domed concrete building that surrounds the reactor core in a pressurized water reactor (PWR) nuclear power plant.

continuous supports: A type of structural support system in which a single beam of at least two spans is continuous across at least one intermediate support.

control rod: In nuclear power generation, a boron carbide rod that slows or stops the nuclear chain reaction by absorbing neutrons when inserted into the reactor core.

convection: Heat transfer through the movement of a liquid or gas.

control channel: In a cellular network, a communications channel that is used to monitor the locations of mobile devices, establish connections, and coordinate handoffs between cells.

copper sulfate: A chemical used to kill algae contamination in a water supply reservoir.

crankcase: In an automobile engine, an enclosure at the bottom of the engine block that houses the crankshaft.

crankshaft: In an automobile engine, a shaft that converts the reciprocating motion of a piston into rotary motion for transmission of power to the drive shaft.

crawl space foundation: A type of building foundation for which the first floor is a wooden platform, raised slightly above ground level, with no basement.

cross-section: The geometric shape of the face created by making a hypothetical cut perpendicular to the longitudinal axis of a structural element, roadway, etc.

crown gear: A large gear with teeth oriented perpendicular to the plane of the gear.

curb valve: An exterior valve that can be used to cut off the water supply to an individual building.

current: The flow of electrons through a conductor when subjected to a voltage. Current is measured in amperes, or amps.

cut-and-cover method: A method of constructing aqueducts and tunnels. The tunnel lining is built at the bottom of a trench and then covered over with compacted soil.

cutout fuse: A fuse that can also be operated manually as a switch.

cycle: (1) In thermodynamics, a sequence of processes that begins and ends at the same state. (2) In traffic engineering, the total period of time, in seconds, required for a signal light to repeat its programmed green-yellow-red sequence in all directions.

cylinder: In an automobile engine, a cylindrical cavity in the engine block that contains a piston.

cylinder head: In an automobile engine, the heavy metal lid that bolts onto the top of the engine block and covers the cylinders.

dam: An engineered structure designed to impound water, generally by blocking the flow of a natural watercourse. A dam creates a reservoir and must control the release of water from that reservoir. Dams are used for water supply, irrigation, flood control, and the generation of hydroelectric power.

damper: A valve or gate that controls the flow of air through a conduit.

deflection: The bending deformation of a beam under transverse loading.

derrick: In an oil or natural gas drilling rig, a steel tower from which the drill string is suspended.

desalination: The process of converting seawater into potable water by removing salt, typically through reverse osmosis.

design hour volume: In highway design, the amount of traffic on a highway during the most heavily congested hour of the day.

design speed: The vehicle speed for which a highway is designed.

design storm: A hypothetical rainstorm with characteristic, statistically derived intensity (measured in inches of rainfall per hour); duration (measured in minutes); and frequency (represented as a recurrence interval in years) that is used as the basis for hydrologic analysis using the rational method.

deviation tower: A power transmission tower located at a major change in the direction of the transmission line.

dielectric: An electrical insulator used between the two charged plates in a capacitor.

diaphragm: (1) A thin disk that vibrates when receiving or producing sound waves, as in a microphone or speaker. (2) A cross-frame used to connect parallel beams or girders together in a structural system.

differential: A mechanical device that performs three different functions: allocating power from the driveshaft to two perpendicular axle shafts, increasing the gear ratio of the drivetrain, and allowing the two drive wheels to rotate at different speeds when the vehicle is negotiating a turn.

digital: In telecommunications, a signal that is made up of a series of on-off pulses, representing ones and zeroes.

dip pole: A utility pole at which a distribution feeder is directed underground.

direct current (DC): A steady, unvarying current, as is produced by a battery.

direct solar heat gain: The process by which the Sun's thermal radiation enters a building through windows; impinges on floors, walls, and furniture; and is reradiated back into the interior space as heat.

discoverability: In user-centered design, a set of characteristics that communicates what actions are possible and how they're to be performed. Designers achieve discoverability through incorporation of affordances, signifiers, mapping, constraints, and feedback into their designs.

disk brake: An automotive braking system in which a pair of hydraulically operated brake pads are forced against a disk to reduce the speed of the vehicle.

disinfection: In water treatment, the use of chlorine, ultraviolet light, or ozone to kill bacteria and viruses in raw water.

displacement: In an automobile engine, the volume swept by the piston as it moves from bottom dead center to top dead center.

distribution: (1) The movement of potable water from a local reservoir or water treatment facility to consumers. (2) The movement of electrical power from a substation to consumers.

dog clutch: In an automotive transmission, a toothed collar that locks a transmission gear to the driveshaft.

downcomer: A vertical pipe that circulates hot water from the steam drum back to the boiler in a steam power plant.

down-hole drilling motor: An oil or natural gas drilling rig in which the motor driving the drilling bit is located at the bottom of the borehole. A down-hole drilling motor provides improved control of the bit and thus is used for horizontal drilling.

downlink: A radio signal transmitted by a satellite to Earth.

drain field: A component of an on-site septic system that receives wastewater from a septic tank and discharges it into the surrounding soil. A series of perforated pipes surrounded by a bed of crushed stone and covered with soil, the drain field promotes filtration and biological treatment of wastewater flowing through the system.

drill collar: In an oil or natural gas drilling rig, a heavy section of pipe located at the bottom of the drill string and immediately above the bit. Drill collars provide the weight needed to drive the drill bit downward through solid rock.

drill string: A series of hollow pipes connected together with threaded couplers that is used to drill the borehole for an oil or natural gas well.

drilling mud: In an oil or natural gas drilling rig, a mixture of water and bentonite clay that is used to lubricate the drilling bit and to carry the rock cutting back up to the surface.

drilling rig: A mechanical system used to drill deep into the Earth's crust to extract petroleum and natural gas.

drip edge: Metal flashing applied to the edges of a roof to prevent water from infiltrating beneath the protective roof membrane and to direct rainwater into the rain gutters.

drivetrain: An integrated series of automotive components that transmit mechanical power from the engine to the drive wheels. The drivetrain consists of the flywheel, clutch, transmission, driveshaft, differential, and drive axles.

driveshaft: In an automobile drivetrain, a shaft that connects the transmission to the differential.

DS-0: Specification for the standard voice channel used in the public switched telephone network (PSTN)—a bandwidth of 4000 hertz and a bit rate of 64,000 bits per second.

drum brake: An automotive braking system in which a pair of hydraulically operated brake shoes are forced against the inner surface of a drum to reduce the speed of the vehicle.

drywall: A panel composed of gypsum sandwiched between two layers of cardboard that is used as a fire-resistant inner layer of the building envelope.

dual-tone multi-frequency signaling (DTMF): The system used to generate tones in touch-tone dialing. In DTMF, a different audio frequency is assigned to each row and column of the standard four-by-three telephone keypad.

ductless mini-split: A small, wall-mounted heat pump that blows hot or cold air directly into the conditioned space, with no ducts.

dump truck: A piece of construction equipment that is used for moving soil over long distances.

earth dam: A gravity dam that uses soil as its primary fill material.

earth sheltering: In architectural design, the practice of embedding one or more walls of a building within a hillside to reduce daily fluctuations in indoor air temperature.

earthwork: The process of re-forming the topographic contours of a project site for compatibility with the intended land use. Also called **grading**.

eccentricity: The extent to which an ellipse deviates from a circle.

efficiency: In thermodynamics, a dimensionless measure of the effectiveness of an energy-conversion process in a device that uses thermal energy—e.g., an engine, a boiler, a furnace, or a refrigerator. In general, thermodynamic efficiency is calculated as a ratio of output to input and thus is always a number between 0 and 1 (or between 0% and 100%). Also called **thermal efficiency**.

elastic energy: A form of energy associated with the deformation of a material. Also called **strain energy**.

electrical energy: A form of potential energy associated with a difference in voltage.

electrical system: A building subsystem that provides electrical power to outlets, light fixtures, appliances, control systems, and other devices.

electromagnet: A magnet that uses the magnetic field produced by an electrical current flowing through a conductor.

electromagnetic induction: The generation of an electric voltage in a conductor that is exposed to a varying magnetic field.

electromagnetic radiation: A type of radiant energy emitted by current flowing through a conductor and other electromagnetic processes.

electromagnetic spectrum: The range of frequencies associated with electromagnetic radiation.

electrostatic precipitator: A device used to remove ash from the exhaust stream of a coal-fired power plant.

end-of-train device: A piece of monitoring equipment mounted on the rear of the last car in a train. The device continuously monitors speed and braking system pressure, and it transmits these data by radio to the cab. Also called a **flashing rear-end device (FRED)**.

energy density: The amount of usable energy stored in a material per unit volume of that material.

engine block: In an automobile engine, the solid block of iron or aluminum that incorporates the cylinders.

engineering: The application of math, science, technology, and experience to create a system, component, or process that serves our society.

equilibrium: (1) In mechanics, the condition in which all forces acting on a body or system are in balance. Mathematically, for a body in equilibrium,

the vector sum of all forces acting on the body equals zero. (2) In thermodynamics, the condition in which all properties of a system are unchanging.

evaporator: A device that changes a liquid to a vapor by transferring heat into the fluid.

exciter: A small generator that produces the electricity required to power the electromagnets on the rotor of a larger power plant generator.

expansion valve: A device that reduces the pressure of a fluid.

fatigue: The progressive accumulation of damage in metals subjected to repetitive loading.

fault: Any abnormal electric current.

feathering: In wind power generation, the process of changing the angle of the rotor blades such that the rotor does not rotate.

feedback: In user-centered design, responsive information indicating that the user's interaction with the object or device was or was not correct.

feeder: A main electrical power supply line in either a power transmission or distribution system.

fenestration: The sizes, locations, and types of windows in an architectural design.

fiber-optic communication: Transmission of information by directing a digitally encoded light beam through a tiny fiber of glass.

fiberglass batting: A common form of thermal insulation used in residential construction.

fill: In power generation, an open web of plastic used in a cooling tower to promote the evaporative cooling of water.

filtration: In water treatment, the use of a filter composed of horizontal layers of gravel, sand, and anthracite coal to remove particulate matter and volatile organic chemicals from raw water.

final drive: In an automotive differential, the pinion and crown gears.

fissile material: A material (e.g., uranium 235) that is capable of sustaining the chain reaction associated with nuclear fission.

fixture: In a plumbing system, a device that draws clean water from the water distribution system and discharges wastewater into the sewage system without allowing any flow in the opposite direction.

flange: (1) One of two horizontal elements forming the top and bottom of an I-shaped structural element. (2) The raised edge on the inside of a steel railcar wheel.

flapper-flush valve: In a standard flush toilet, a hinged stopper that closes off the flush tube connecting the tank to the bowl. Opening the flapper-flush valve causes the toilet to flush.

flashing: A strip of sheet metal or plastic configured to prevent leaks at intersections and penetrations in wall and roof surfaces.

flashover: An electrical phenomenon caused by a large voltage difference between two closely spaced conductors. If the voltage difference is large enough to overcome the electrical resistance of the air between the two conductors, current—in the form of a white-hot electrical arc—jumps the gap between them.

flexible pavement: A road structure typically consisting of a layer of asphalt placed on a layered base of compacted fill.

flexure: Bending of a structural element characterized by compression on the concave face of the element and tension on the convex face.

flocculation: In water treatment, the process by which suspended particles clump together under the action of a chemical coagulant. Each resulting clump of particulate matter is called a floc.

fluid: A liquid or gas.

flywheel: In an automobile drivetrain, a heavy disk that provides for steady rotation of the crankshaft in response to repetitive impulsive torques applied by the pistons.

focus: One of two points on which the geometric construction of an ellipse are based.

footing: A foundation element that distributes the weight of a structure to the soil below. Wall footings and column footings support walls and columns, respectively.

footprint: A satellite antenna's designated coverage area on the Earth's surface.

force: A push or pull applied to an object. A force is defined in terms of both magnitude and direction.

foundation: An assemblage of building elements that transmit loads from the structural system into the Earth.

four-stroke cycle: The process by which an internal combustion engine produces mechanical power through a series of four piston strokes: intake, compression, power, and exhaust.

fractionating: An industrial process by which crude oil is separated into its constituent hydrocarbons.

freight yard: A railroad hub at which incoming trains are broken apart and reorganized into outgoing trains based on the destination of their cargo.

frequency: For any cyclic phenomenon, the number of alternating cycles occurring within a given period of time. Frequency is expressed in hertz or cycles per second and is the reciprocal of the period.

frequency-division multiple access: A system for wireless communication in which multiple conversations are transmitted independently between various mobile devices and a cellular base station on different frequencies.

frequency-division multiplexing: A form of multiplexing in which the total bandwidth available for transmission is subdivided into a series of nonoverlapping frequency subbands, each of which constitutes a separate communications channel.

frequency modulation (FM): A form of modulation in which the frequency of the carrier wave is modified to represent the voice signal.

friction: A resisting force developed at the interface between two bodies. The friction force is oriented parallel to the contact surface in the direction that opposes motion.

frost heave: The upward swelling of soil caused when water within the soil freezes and expands in the winter.

fuel rod: In nuclear power generation, a metal tube containing pellets of fissile material. Bundles of fuel rods are combined to form the core of a nuclear reactor.

fulcrum: The pivot on which a lever rotates.

full-duplex communication: A form of communication that allows for simultaneous transmission and reception.

fuse: A device that interrupts electric current in a conductor to prevent damage to the system in the event of a short circuit or other abnormal event. Unlike a circuit breaker, a fuse cannot be operated manually and must be replaced after it has operated once.

gear ratio: The ratio of the numbers of teeth on two meshed gears. The gear ratio corresponds to the mechanical advantage of the gears.

general packet radio service: A packet-switched network that is overlaid on the circuit-switched phone network and handles all Internet data passing between mobile devices and the Internet.

generator: A device that converts the kinetic energy of a rotating shaft into electrical energy.

geo-membrane: A flexible, puncture-resistant, low-permeability plastic sheet that is used in the liner of a sanitary landfill.

geotextile: A durable, permeable synthetic fabric that is used as a filter in a sanitary landfill.

geostationary orbit (GEO): A circular orbit with an altitude of 22,236 miles above the Earth's surface. A satellite in a GEO orbits the Earth in exactly one sidereal day.

geothermal heat pump: A heat pump that uses the earth, rather than the outside air, as its heat source in the winter and its heat sink in the summer.

geothermal power generation: The generation of electrical power from naturally occurring heat below the Earth's surface.

girder: A main beam to which load is transmitted from other elements of a structural system.

global positioning system (GPS): A satellite-based system for navigation on the surface of the Earth.

governor: In an automatic transmission, a device that controls the flow of hydraulic fluid in response to the speed of the rotating shaft to which it is fixed.

grade: (1) A standardized quality rating for commercial lumber. Higher grades of wood have fewer defects and, thus, higher strength. (2) Ground level (as in slab on grade and railroad grade crossing). (3) The slope of a surface, typically measured as a ratio of vertical to horizontal distance and expressed as a percentage. Also called a **gradient**.

grade-separated intersection: In traffic engineering, an intersection at which traffic streams cross at two or more different levels. Also called an **interchange**.

grade tangent: In highway design, a straight-line segment in the vertical alignment of a road.

grade tunnel: An aqueduct tunnel that carries the channel through a mountain while maintaining a constant gradient.

gradient: The slope of a surface, typically measured as a ratio of vertical to horizontal distance and expressed as a percentage. Also called a **grade**.

grading: The process of re-forming the topographic contours of a project site for compatibility with the intended land use. Also called **earthwork**.

gravity dam: A dam that attains its structural stability from its mass, rather than from arch action.

gravity load: A load caused by weight (e.g., of snow, occupants, furnishings, or the structure itself).

grid: A network of power plants, substations, and transmission lines serving a large geographic area.

ground fault: An electrical fault in which current bypasses the normal load and flows into the earth.

groundwater: Water that percolates down through the soil and accumulates in an underground aquifer.

handoff: In a cellular network, the transfer of control of a mobile device from one cell to another.

hard water: Water containing dissolved calcium or magnesium, typically from natural sources.

header: A structural element used to frame an opening in a floor platform or wall panel.

heat: Thermal energy transferred from a region of higher temperature to a region of lower temperature.

heat exchanger: A device for transferring heat from one fluid to another, usually without allowing them to mix.

heat flux: The rate of heat transfer from a warm region to a colder region.

heat pump: A device that uses the vapor-compression refrigeration cycle to heat an enclosed space.

heat recovery ventilator (HRV): A ventilation device that improves energy efficiency by transferring heat between the incoming and outgoing airstreams.

heavy timber frame construction: A structural system in which wooden columns, beams, and braces form a discrete structural skeleton.

helical gear: A gear with radially oriented teeth, the edges of which are not parallel to the axis of rotation of the gear. In comparison with spur gears, helical gears mesh more fully and run more smoothly.

heliostat: A movable mirror used in solar-thermal power generation.

housewrap: A plastic sheet used to prevent water infiltration through a building envelope.

hot-rolled section: A steel structural element manufactured by heating a block of steel and then forming it into shape with large hydraulically operated rollers.

HVAC: The heating, ventilating, and air-conditioning system for a building.

hybrid coil: A type of transformer that divides an incoming signal among two outgoing branches.

hydraulic control unit: In an automatic transmission, a fluid-powered computer that uses pressurized transmission fluid moving through a series of valves to determine when each shift should occur and to execute the changes of gears.

hydraulic fracturing: The process of using a high-pressure fluid to create fractures in underground rock to facilitate the extraction of oil or natural gas. Fracturing fluid contains proppants, which hold the fractures open after the fluid pressure has been reduced.

hydraulics: A scientific field that is broadly concerned with the mechanical properties and engineering applications of fluids.

hydrocarbon: An organic chemical compound consisting of hydrogen and carbon atoms.

hydroelectric power: Electric power produced by water flowing through a turbine. The source of energy for hydroelectric power is the potential energy stored in water contained at a relatively high elevation behind a dam.

hydrology: The scientific study of the natural movement and distribution of water above, on, and below the surface of the Earth.

hydronic heating: A heating system that operates by circulating hot water from a boiler throughout the heated space.

hydrostatic pressure: Pressure caused by the weight of water. Hydrostatic pressure acts uniformly in all directions. Where water is in contact with a

submerged body, hydrostatic pressure acts perpendicular to the surface of the body.

hypoid bevel gear set: In an automotive differential, a paired pinion and crown gear with specially curved teeth that allow the pinion shaft to be placed below the level of the crown gear shaft.

hysteresis: A built-in lag between input and output in an automatic control system (e.g., a thermostat).

ice dam: An accumulation of ice at the edge of a roof. Water from melting snow and ice can back up behind the ice dam and cause leaks through the roof membrane.

idler: In an automotive transmission, a gear used to reverse the rotation of the driveshaft.

impedance: Electrical resistance to alternating current.

immersed-tube tunnel: A type of tunnel built of multiple tube segments, which are prefabricated on land, floated into position, sunk to the bottom of the watercourse, and connected together.

impulse turbine: A water turbine that operates by directing a stream of water into a series of buckets arranged around the circumference of a rotating wheel, or runner.

inclined plane: A simple machine that allows one to lift an object using less force than the weight of the object.

independent suspension system: An automotive suspension system in which the road-induced motion of one suspension unit does not affect the motion of the other suspension units.

infrastructure: Large-scale technological structures and systems that enhance societal functions, facilitate economic development, and enhance quality of life. The most common infrastructure systems are electrical power,

water supply, wastewater disposal, storm drainage, solid waste disposal, transportation, and telecommunications.

input shaft: In an automobile drivetrain, a shaft that connects the engine to the transmission.

insulator: A material or object that prevents the flow of electric current.

interchange: In traffic engineering, an intersection at which traffic streams cross at two or more different levels. Also called a **grade-separated intersection**.

interconnection: A major regional electric power grid that operates at a synchronized frequency.

intermediate storage facility: A tank for temporary water storage in a water distribution system.

intermodal transportation: A form of freight transportation in which standardized shipping containers are used to move cargo by ship, truck, and train.

internal energy: A form of energy associated with the microscopic motions of the particles that constitute matter.

internal force: A force developed within a structural element in response to one or more applied loads. An internal force can be either tension or compression.

international gateway: In the public switched telephone network (PSTN), a switch through which international calls are routed.

intersection: A traffic structure at which two or more streams of traffic cross each other, with drivers typically having the option to continue on their present route or to switch from one stream to another.

inverted siphon: A type of aqueduct channel in which the water flows through a pipe under pressure from a higher to a lower reservoir. In an inverted siphon, much of the channel is typically below the elevation of the lower reservoir.

isotherm: A line of constant temperature, as on a pressure-volume diagram.

Janney coupler: The mechanism used to connect two railcars together.

joist: One of a series of parallel beams that directly support a floor or deck.

kelly: In an oil or natural gas drilling rig, a four- or six-sided pipe that grips the top of the drill string and drives its rotation.

kinetic energy: The energy associated with a mass in motion.

kinetic friction: The friction force resisting the motion of a body sliding across a surface.

knock: In an automobile engine, premature combustion of the fuel-air mixture in a cylinder before the spark plug fires.

landfill gas: A mixture of methane, carbon dioxide, and small amounts of other gases formed by the decomposition of organic material in a sanitary landfill.

latency: Delay in a telecommunications transmission.

lateral: A pipe that carries wastewater from a soil stack inside a building to a sewer line or on-site septic system.

lateral earth pressure: The horizontal pressure of soil acting on a vertical surface.

lateral-torsional buckling: A structural failure mode in which the compression side of a beam (normally the top) buckles sideways, causing the

beam to twist. Tall, narrow beam cross-sections are particularly vulnerable to lateral-torsional buckling.

layshaft: In an automotive transmission, a shaft that transmits power from the input shaft to the driveshaft.

leachate: A toxic, acidic liquid that accumulates within a sanitary landfill as a result of rainwater percolating down through the solid waste.

lead: A branch railroad line that terminates at a dead end.

leakage current: The unintended flow of electric current over the surface of an insulator, usually due to the presence of moisture, dirt, or salt on the insulator.

lever: A simple machine that converts an applied force to a larger force through rotation about a fulcrum.

light wood frame construction: A structural system consisting of floor platforms and wall panels fabricated from multiple lightweight elements made of standard-sized lumber and fastened with nails.

lightning arrester: In an electrical transmission or distribution system, a device that protects sensitive equipment by routing the power surge caused by a lightning strike into the ground.

line: In the public switched telephone network (PSTN), a telecommunications link designed to support the calling load associated with one person.

live load: The weight of people, furniture, and other movable objects contained within a building.

load: A force applied to a structure. Types of loads include dead load, live load, snow load, wind load, and seismic load.

local exchange: In the public switched telephone network (PSTN), a switch through which all subscribers and private branch exchanges (PBX)

communicate with each other and with other exchanges. The local exchange is typically housed in a building called the central office.

local loop: In telecommunications, a pair of copper wires running from the subscriber's telephone to the local exchange. Also called a **subscriber line**.

local road: A road that provides access within residential areas, commercial districts, etc.

long-wall mining: An underground coal-mining technique in which a track-mounted excavating machine moves along an exposed face of coal, shearing off and collecting a slice of coal as it moves, protected by hydraulically operated overhead shields.

low earth orbit (LEO): A circular orbit with an altitude between 100 and 1240 miles above the Earth's surface.

low-emissive coating: A coating applied to energy-efficient windows to limit heat transfer by radiation.

mapping: In user-centered design, the relationship between controls and the actions they control.

mass diagram: In heavy construction, a graphical tool used to achieve balanced earthwork.

mean speed: In traffic engineering, the average speed of all vehicles passing a point on a highway within a specified period of time, measured in miles per hour.

mechanical advantage: Magnification of effort by a mechanical device.

mechanical properties: Characteristics of a material that describe how the material responds to forces.

mechanics: A branch of science that deals with the effects of forces acting on physical bodies.

meltdown: In nuclear power generation, a failure condition that occurs when one or more nuclear fuel rods exceeds its melting temperature. A meltdown is caused by failure of the reactor cooling system.

methane: A hydrocarbon with chemical formula CH_4 . Methane is the principal component of natural gas and is also produced by the decomposition of organic material.

microphone: A device that converts sound waves into an electrical signal.

microwave communication: Use of very high-frequency electromagnetic radiation for point-to-point communication.

mission payload: The communications package in a communications satellite.

mobile switching center: In a cellular network, a facility that connects to and controls all cellular base stations within a region. The mobile switching center sets up and releases end-to-end calls—both mobile-to-mobile and mobile-to-PSTN calls.

model code: A set of technical standards, guidelines, or specifications promulgated by a professional standards organization but having no legal status or enforcement mechanisms. When a model code is adopted by a government entity through legislation, it becomes a building code.

modulation: In telecommunications, a process by which voice and carrier signals are electronically mixed for transmission.

moment: The tendency of a force to cause rotation, expressed in units of force times distance.

mortise-and-tenon joint: A traditional method of joining beams and columns in a heavy timber framed structural system.

multiplexing: In telecommunications, a process by which multiple signals or data streams are combined into one signal for transmission over a shared medium.

nacelle: A streamlined housing that encloses the generator of a wind turbine.

navigation equation: In the global positioning system, the equation used to calculate the position of the receiver on the Earth's surface.

net-zero-energy home: A residential building that requires no net input of energy over the course of a year.

Newton's first law: An object at rest (or in motion at constant velocity) will remain at rest (or in motion at constant velocity) unless it is acted on by an unbalanced force.

Newton's second law: The force acting on a body is equal to its mass times its acceleration.

Newton's third law: For every action, there is an equal and opposite reaction.

neutral: An electrical conductor that provides a return path to complete a circuit.

noise: In telecommunications, the progressive corruption of a signal as it moves along a transmission path.

nonassociated gas: Natural gas that is found in gas fields and in coal beds separate from petroleum deposits.

normal force: A force developed at the interface between two bodies. The normal force is always oriented perpendicular to the contact surface.

nuclear chain reaction: A self-sustaining process that occurs when neutrons emitted by the fission of atomic nuclei encounter adjacent nuclei and cause them to split and emit more neutrons.

nuclear energy: A form of energy associated with the bonds between the particles that constitute the atomic nucleus.

nuclear fission: A process in which an atomic nucleus splits into lighter nuclei and releases energy. In a fissile material, fission can occur spontaneously, or it can occur when the nucleus absorbs a free neutron.

Ohm's law: Voltage = current \times resistance.

on-site septic system: A wastewater treatment system for a single residence. A typical on-site septic system consists of a septic tank and a drain field.

open-cast mining: A form of surface mining used to extract minerals from deposits relatively close to the surface. Also called **strip mining**.

open-channel flow: In hydraulics, a category of flow in which the conduit is partially full and the upper surface of the liquid is at atmospheric pressure.

orbital period: The time required for one orbit.

orbital station: The longitude to which a satellite in a geostationary orbit is assigned.

oriented strand board (OSB): An engineered wood panel formed by compressing layers of wood strands and adhesive. OSB often serves as a substitute for plywood in modern residential construction.

Otto cycle: A thermodynamic cycle used to model the operation of an internal combustion engine.

outfall sewer: A pipe that discharges treated wastewater into a natural watercourse.

outlet: The point at which storm runoff departs from a watershed.

outlet works: A conduit and associated equipment (gates, valves, etc.) that is used to control the release of water from a reservoir through a dam.

overdrive: In an automotive transmission, a gear ratio for which the driveshaft rotates faster than the input shaft.

packet-switched network: A network in which a transmission is broken up into many small chunks (called packets), which are then transmitted independently across a shared network, with each packet potentially following a different route.

passive solar design: A holistic building design approach in which the location, orientation, architectural configuration, and interior features of a building are chosen with a focus on maximizing solar heat gain in the winter and minimizing it in the summer.

penstock: In hydroelectric power generation, a large tube that transmits water at high velocity from the reservoir to a turbine.

perigee: The lowest point in an elliptical orbit.

period: For any cyclic phenomenon, the time required for one full cycle. The period is the reciprocal of the frequency.

petroleum: A naturally occurring mixture of hydrocarbons, organic compounds consisting entirely of hydrogen and carbon atoms.

phase: In traffic engineering, the portion of a signal-light cycle in which the right-of-way is uniquely assigned to one or more traffic streams.

photovoltaic effect: An effect that occurs when photons impinging on a semiconductor (e.g., silicon) excite electrons to higher states of energy. In a photovoltaic device, these free electrons are captured in an adjoining material, where they constitute an electric current.

photovoltaics: Technologies that use solar cells to convert solar radiation directly into electricity through the photovoltaic effect.

pin: A structural support that permits rotation but restrains both horizontal and vertical movement.

pinion: A small gear that is typically positioned on the end of a shaft.

pipe flow: In hydraulics, a category of flow in which the liquid completely fills the conduit and flows under pressure.

piston: In an automobile engine, a cylindrical element is driven in reciprocating motion to produce mechanical power.

plain old telephone service (POTS): The traditional landline telephone system.

planet carrier: In a planetary gearset, the fixture on which one or more planet gears are mounted.

planetary gearset: An arrangement of one or more sun gears, each of which rotates on a fixed shaft, and planet gears, which revolve around the sun gears.

plate girder: A girder fabricated by welding or riveting individual steel plates together, typically into an I-shaped cross-section.

platform-framed construction: The most common form of modern light wood frame construction, named for the modular floor platform that serves as a base for the construction of each story.

plenum: The main air supply duct in a forced-air heating system.

plumbing system: A building subsystem that provides clean water to fixtures and transmits wastewater outside the building for disposal.

potable water: Water that is safe for drinking.

potential energy: The energy associated with the elevation of a mass.

power: (1) The rate at which work is done, measured in units of force \times distance \div time. (2) Voltage \times current, measured in watts (or volt-amps).

pressure tunnel: A type of aqueduct channel in which the water flows through a deep underground channel that passes beneath an obstacle. A pressure tunnel is a form of inverted siphon.

pressure-volume diagram: In thermodynamics, a graphical representation of equilibrium states or thermodynamic processes in terms of pressure, volume, and temperature.

pressurized water reactor (PWR): A type of nuclear power plant in which the reactor coolant water is kept at high pressure, such that it never boils. In a PWR, the coolant water and the water that drives the steam turbines are kept in separate self-contained loops (called primary and secondary) to minimize the possibility of contamination.

prestressed concrete: A construction method in which prestretched steel reinforcing cables (called tendons) transfer compressive stress to a concrete structural element to control cracking and reduce deflections. The two methods of prestressing concrete are pretensioning and posttensioning.

primary loop: The loop of piping through which reactor coolant water is circulated in a pressurized water reactor (PWR). Heat is transferred from the primary loop to the secondary loop in a steam generator.

primary treatment: In sewage treatment, the removal of floatable contaminants and sludge from wastewater in a sedimentation tank (also called a primary clarifier).

private branch exchange (PBX): In telecommunications, a switch that allows both internal communication between any two connected subscribers and external communication through the local exchange.

property: In thermodynamics, a characteristic (e.g., mass, volume, pressure, temperature, internal energy) that can be measured and expressed quantitatively for the system as a whole at a given point in time.

proppant: In the process of hydraulic fracturing, a solid particulate material designed to keep a fracture open to facilitate the extraction of oil or natural gas.

public switched telephone network (PSTN): A worldwide telecommunications system consisting of conventional telephone lines, fiber-optic cables, microwave links, communications satellites, and undersea cables that are interconnected at exchanges using standardized communications protocols.

pulley: A simple machine that changes the direction of a rope or cable.

R-value: A quantitative measure of thermal resistance.

racking: The distortion of a frame due to lateral loading.

radial tire: A vehicle tire with its internal reinforcing plies oriented in the radial direction.

radiant energy: A form of energy associated with light and other forms of electromagnetic radiation.

radiant floor heating: A hydronic heating system in which hot water is circulated through the floor of a building.

rake: The inclined edge of a peaked roof.

rational method: An analysis methodology for calculating maximum rate of storm runoff (measured in cubic feet per second) from a watershed during a specified design storm.

raw water: Untreated water obtained from a natural source.

reaction turbine: A water turbine in which the runner is horizontally mounted and fully enclosed within a spiral-shaped casing. Water enters the turbine tangentially along the circumference of the casing and exits downward

through the center. Unlike an impulse turbine, the runner of a reaction turbine is always fully submerged.

reaction wheel: An electric-powered wheel that is used for attitude control in a satellite.

reactor core: In nuclear power generation, the vessel in which the nuclear reaction takes place. The reactor core contains nuclear fuel rods and control rods.

reciprocating motion: Cyclic up-and-down or back-and-forth motion that is characteristic of a piston in a cylinder.

recloser: A circuit breaker that can automatically reclose the circuit after it has been opened due to a short circuit or other abnormal condition.

refrigerant: A fluid used to facilitate the transfer of heat in the vapor-compression refrigeration cycle.

regenerative repeater: In digital communications, a device used to eliminate the adverse effects of noise by regenerating a new noise-free signal at regular intervals along the transmission path.

register: A grill with shutters for controlling the flow of air in a heating or air-conditioning system.

reheater: In a steam power plant, a device that transfers heat from the furnace exhaust gases to the steam en route from the high-pressure turbine to the intermediate-pressure turbine.

remote concentrator: In the public switched telephone network (PSTN), a low-level switch in which multiple subscriber lines are multiplexed into a single trunk for transmission to the local exchange. At a remote concentrator, the signal is usually converted from analog to digital as well.

renewable energy: Energy produced from resources that are naturally replenished on a human timescale.

repeater: In satellite communications, a device that receives an uplink, boosts the strength of the signal, shifts its frequency, and retransmits it back to Earth as a downlink. A repeater incorporates a receiver and multiple transponders.

reservoir rock: Porous underground strata of limestone and sandstone in which petroleum and natural gas accumulate.

resistance: The tendency of a conductor or other object to impede the flow of electric current through it. Resistance is measured in ohms.

resistive heating: The dissipation of electrical energy as heat, resulting from resistance to the flow of current.

resistivity: The tendency of a material to impede the flow of electric current through it.

reverse osmosis: The process of removing salt from seawater by forcing the water through a membrane under high pressure.

rigid pavement: A road structure that typically consists of a reinforced concrete slab placed on a layer of compacted fill.

rings: In an automobile engine, metal rings mounted near the top of a piston to provide a tight seal between the piston and its associated cylinder.

riser: A vertically oriented water-filled steel tube integrated within the walls of the furnace in a steam power plant. A series of closely spaced risers form the walls of the boiler.

roadholding: The ability of an automotive suspension system to keep the tires in contact with the road surface as the vehicle moves.

road isolation: The ability of an automotive suspension system to absorb the impacts caused by irregularities in the road surface.

rock-fill dam: A gravity dam that uses rock as its primary fill material.

roller: A structural support that permits rotation and horizontal movement but restrains vertical movement.

room-and-pillar method: An underground coal-mining technique in which regularly spaced pillars of solid coal are left intact to hold up the roof of the excavation.

rotational moment of inertia: The resistance of a body to rotation.

rotor: (1) In a steam turbine, a set of angled blades that rotates with the turbine shaft. The rotor interacts with a stator to produce shaft power. One stator and one rotor constitute one stage of the turbine. (2) In a generator, a rotating element on which one or more magnets are mounted. The rotor produces a varying magnetic field that induces an electrical current in the stator. (3) In a wind turbine, the assembly of rotating blades that drives the generator shaft.

router: A device that manages the flow of information through a node in a packet-switched network.

runner: The rotating element of a water turbine.

sag: For a cable suspended between two supports, the difference in elevation between the supports and the lowest point along the cable.

sanitary landfill: A solid waste disposal facility designed to return the waste to the Earth in a way that maximizes the use of available land and minimizes harm to the environment.

sanitary sewer: A municipal wastewater disposal system consisting of progressively larger pipes called branches, trunks, and interceptors.

saturated liquid: The thermodynamic state at which a fluid has just begun to boil but is still 100% liquid.

saturated vapor: The thermodynamic state at which a fluid is at its boiling point and is 100% vapor.

scraper: A piece of construction equipment that is used for moving soil over moderate distances. A scraper moves soil by scooping it up with its hydraulically operated pan.

screw: A simple machine that converts rotational motion into linear motion or converts a moment into a linear force directed along the length of the screw.

scrubber: A device used to remove sulfur dioxide from the exhaust stream of a coal-fired power plant.

secondary loop: The loop of piping through which the steam that drives the turbines is circulated in a pressurized water reactor (PWR). Heat is transferred from the primary loop to the secondary loop in a steam generator.

secondary treatment: In sewage treatment, the reduction of biochemical oxygen demand (BOD) in wastewater through the use of natural biological processes.

selective catalytic reduction: A process used to remove nitrogen oxides from the exhaust stream of a coal-fired power plant.

septic tank: A closed, watertight container that is used to remove suspended solids from wastewater in an on-site septic system.

service drop: An electrical line that carries power into a building.

servo: In an automatic transmission, a spring-loaded hydraulic piston that is used to actuate a brake band or clutch.

sewage lift station: A pump used to lift the flow of sewage to a higher elevation in situations where continuous downhill flow are not feasible.

shale: A fine-grained sedimentary rock that is formed primarily from clay minerals and quartz.

shale gas: Natural gas that is found within and extracted from shale, usually through the process of hydraulic fracturing.

sheathing: A structural sheet—normally plywood or oriented strand board—that covers the outside of a wall panel or roof framing in platform-framed construction.

shield wire: A wire suspended above electrical power transmission lines to protect against lightning strikes.

shock absorber: A device that damps out vibrations.

short circuit: An electrical fault in which the current bypasses the normal load.

short message service (SMS): A wireless text-messaging service introduced with the 2G cellular standard.

shotcrete: Concrete that is sprayed onto a surface.

sidereal day: The time required for the Earth to complete one full rotation with respect to a nonrotating frame of reference. A sidereal day is 23.93 hours long.

siding: A branch railroad line that splits off of a main line, runs parallel to it for a distance, and then rejoins it.

sight distance: In traffic engineering, the distance a driver must be able to see in order to make a decision and then act on that decision without risk of collision.

signifier: In user-centered design, an explicit message about how an object is to be used.

simple supports: A type of structural support system consisting of a pin at one end of an element and a roller at the other end.

slab on grade: A type of building foundation for which the first floor is a concrete slab placed at ground level, with no basement.

slurry: A mixture of water and cement, mud, or another insoluble material.

soil stack: A large vertical pipe that collects all wastewater from a plumbing system and delivers it to the municipal sewage system or on-site septic system.

solar heat gain coefficient: A metric used in the window rating system of the National Fenestration Rating Council. This coefficient measures the fraction of solar radiation that is admitted through a window.

solar panel: A device for generating electricity through the photovoltaic effect. A solar panel consists of an array of solar cells.

solar power: The conversion of solar radiation into electrical energy. The two principal forms of solar power are solar-thermal power and photovoltaics.

solar-thermal power: A form of solar power generation in which mirrors are used to concentrate the Sun's rays onto a single point, producing enough heat to generate electricity.

source rock: Fine-grained shale in which hydrocarbons form deep under the surface of the Earth.

space-division multiplexing: A form of multiplexing in which a geographic region is subdivided into a regular grid of smaller areas called cells, each with its own antenna and base station.

speaker: A device that converts an electrical signal into sound waves.

spillway: A structure that facilitates the controlled release of surplus water from a reservoir to prevent the associated dam from being overtopped.

spring: (1) A source of water occurring where an aquifer intercepts the ground surface. (2) A mechanical device that provides a resisting force proportional to its deformation in either tension or compression.

spur gear: A standard gear with radially oriented teeth, the edges of which are parallel to the axis of rotation of the gear.

spur line: An electric power distribution line carrying a single phase.

stack ventilation: In architectural design, the practice of using upper-level openings to exhaust naturally rising hot air.

standard gravitational parameter: In orbital mechanics, a mathematical constant used in the calculation of the orbital velocity and period of a satellite. The standard gravitational parameter is equal to the universal gravitational constant times the mass of the planet about which the satellite is orbiting.

standards organization: A nonprofit professional society that formulates one or more model codes.

standup time: The length of time that the walls and ceiling of an excavation will support themselves without structural augmentation.

static friction: The friction force between two stationary bodies or between a stationary body and a surface.

stator: (1) In a steam turbine, a set of angled blades that are fixed to the turbine casing. The stator interacts with a rotor to produce shaft power. One stator and one rotor constitute one stage of the turbine. (2) In a generator, the stationary coil in which an electrical current is induced by the rotor.

steam drum: A device that separates high-pressure steam from boiling water in a steam power plant.

steam generator: A device that transfers heat from the primary loop to the secondary loop in a pressurized water reactor.

steam turbine: A mechanical device that converts the internal energy in steam into the kinetic energy of a rotating shaft.

stilling basin: A pool at the bottom of a spillway that is used to dissipate the energy of water flowing over the spillway to prevent scouring at the base of the associated dam.

stopping sight distance: In highway design, the distance required for a driver of a moving car to recognize a hazard in the roadway and bring the vehicle to a halt before reaching the hazard.

storm drainage system: An engineered system that captures the surface runoff resulting from precipitation and channels it into a natural watercourse.

storm sewer: A network of underground pipes that collects storm water and conveys it to a nearby watercourse, lake, or ocean.

strength: The maximum force a structural element can carry before it fails. Strength can be defined for both tension and compression.

stress: The intensity of internal force within a structural element, defined in terms of force per area (e.g., pounds per square inch).

stroke: In an automobile engine, the distance a piston moves within its cylinder.

structural insulated panel (SIP): A recently developed technology for highly energy-efficient residential construction. A SIP serves as both structure and enclosure.

structural system: An assemblage of structural elements—e.g., beams, columns, rafters, trusses, wall panels, and connections—designed to carry load safely.

subfloor: A structural floor panel that is normally made of plywood or oriented strand board and is supported on joists.

subscriber line: In telecommunications, a pair of copper wires running from the subscriber's telephone to the local exchange. Also called the **local loop**.

substation: A facility that serves as a node in an electrical power transmission or distribution network. Substations may incorporate switches (or circuit breakers), transformers, and a variety of other devices for power management.

sump pump: An electric pump that removes groundwater from beneath the floor slab of a building.

superelevation: In highway design, the angle at which a roadway is banked in a horizontal curve.

superheater: In a steam power plant, a device that transfers heat from the furnace exhaust gases to the steam en route from the steam drum to the turbines.

suspension: In an automobile, a mechanical system that supports the weight of the vehicle, provides road isolation, provides roadholding, and prevents excessive body roll.

sustainable engineering: Engineering that meets the needs of the present without compromising the ability of future generations to meet their own needs.

switch: In a telecommunications network, a computer that is used to establish and manage connections between transmission lines. Switches are located at nodes in a circuit-switched network.

switchyard: A facility that connects a power plant to its associated power transmission system. The principal function of the switchyard is to increase voltage for long-distance transmission.

swivel: In an oil or natural gas drilling rig, a rotating fitting from which the drill string is suspended.

synchromesh: In an automotive transmission, a device that synchronizes the rotational speeds of a dog clutch and its paired gear, allowing them to mesh.

system: In thermodynamics, a fixed quantity of matter contained within a well-defined boundary.

tailrace: The pipe through which water is carried away from a reaction turbine.

tandem exchange: In the public switched telephone network (PSTN), a switch located immediately above the local exchange in the network hierarchy.

tangent: In highway design, a straight-line segment in the horizontal alignment of a road.

target cell: In a cellular network, a cell that acquires control of a mobile device during a handoff.

technology: The product of engineering.

teleport: A ground-based communications port that provides customers with access to satellite communications.

tendon: A high-strength steel reinforcing cable that is used in prestressed concrete.

tension: An internal force or stress that causes elongation of a structural element.

thermal deformation: The tendency of a material to expand when heated and contract when cooled.

thermal mass: An object's capacity to store heat.

thermodynamic efficiency: A dimensionless measure of the effectiveness of an energy-conversion process in a device that uses thermal energy—e.g.,

an engine, a boiler, a furnace, or a refrigerator. In general, thermodynamic efficiency is calculated as a ratio of output to input and thus is always a number between 0 and 1 (or between 0% and 100%). Also called **thermal efficiency**.

thermostat: A mechanical or electronic device used to control temperature.

three-phase power: Electric power generated, transmitted, and distributed through three conductors, each carrying an alternating current (AC) of the same frequency and voltage, but each out of phase with the other two by 120°.

thermal bridge: A pathway through a wall or other building element that provides reduced thermal resistance.

thermal radiation: Heat transfer through electromagnetic waves emitted by a substance.

thermal resistance: The extent to which a particular material resists the movement of heat through it.

time-division multiple access: A system for wireless communication in which the available frequency spectrum is first subdivided into channels, and then, within each channel, multiple communication devices are each assigned a specific time slot for transmission.

time-division multiplexing: A form of multiplexing in which multiple signals are transmitted over a common path by assigning a unique sequential time slot to each signal.

time of concentration: The time it takes for a drop of water to flow from the most remote point in the watershed to the outlet.

torque: A moment applied to a shaft, measured in units of force times distance.

torque converter: In an automatic transmission, a device that allows the engine to keep running when the vehicle comes to a stop and that cushions abrupt changes in the relative speeds of the input and output shafts during gear changes. The three main components of a torque converter are the impeller, turbine, and stator.

traction: The accelerating, braking, and turning forces generated at the interface between a vehicle tire and the surface on which it is rolling.

traffic control feature: A signal light, traffic sign, or pavement marker designed to ensure the orderly, predictable, and safe movement of vehicles by formally assigning the right-of-way to various routes through the intersection.

traffic density: In traffic engineering, the number of vehicles traveling on a specific length of highway at a particular instant in time, measured in vehicles per mile.

traffic flow: In traffic engineering, the hourly rate at which vehicles pass a specific point on a highway, measured in vehicles per hour.

traffic volume: In highway design, the amount of traffic on a highway, measured in vehicles per day.

transaxle: An automotive transmission and differential integrated into a single unit.

transformer: A device that either raises or lowers electric voltage.

transmission: (1) The movement of electrical power over long distances from power-generating facilities to the regions in which the power will be consumed. A transmission line terminates at a substation. (2) In an automobile drivetrain, a device that keeps the engine rotating within its most efficient range of operation while providing adequate torque across the full range of vehicle speeds.

truss: A structural system composed of slender elements arranged in interconnected triangles. Truss elements carry load primarily in tension or compression.

toll center: In the public switched telephone network (PSTN), a switch through which long-distance calls are routed.

torsion: The twisting of a structural element around its longitudinal axis.

transponder: In satellite communications, a device that filters out a particular signal from an uplink, amplifies that signal, shifts its frequency, and then retransmits it as a downlink. Multiple transponders are incorporated within the repeater of a satellite.

trunk: In the public switched telephone network (PSTN), a telecommunications link designed to support the calling load associated with multiple users.

tunnel lining: A structural shell that covers the inner face of a tunnel, resists soil and water pressure, and preserves the stability of the tunnel excavation.

turbine: An engine that produces continuous power by means of a fast-moving flow of water, steam, gas, or air driving a rotor fitted with vanes or blades.

turnout: A railroad switch at which one rail line branches off from another.

twisted pair: Two twisted copper wires that are used for subscriber lines in the public switched telephone network (PSTN).

U-factor: Thermal transmittance. The U-factor is the mathematical reciprocal of the R-value.

underground mining: The excavation of tunnels and shafts to access mineral deposits deep under the surface of the Earth.

universal joint: A mechanical connection between two shafts that allows the transmission of torque between shafts, even when one shaft is angled with respect to the other.

uplink: A radio signal transmitted to a satellite.

uranium 235: The most commonly used fissile material for nuclear power generation.

vapor: The gaseous phase of a substance.

vapor-compression refrigeration: The thermodynamic cycle that serves as the basis for most modern refrigeration.

vapor dome: On a pressure-volume diagram, the dome-shaped transition region between the liquid and vapor phases.

vector: A mathematical quantity that has both magnitude and direction.

vehicle flow rate: In highway design, the amount of traffic on a highway, measured in vehicles per hour per lane.

viscosity: The resistance of a fluid to flow.

visible transmittance: A metric used in the window rating system of the National Fenestration Rating Council. This coefficient measures the fraction of visible light that passes through the glass.

voltage: A difference in electrical potential between two points, measured in volts. Voltage causes current to flow through a circuit.

voltage regulator: A device that makes minor adjustments to output voltage at an electric substation.

wastewater: All liquid and solid material that drains from plumbing fixtures in a building or other facility.

water distribution: The delivery of treated water to consumers.

water hammer: A shock that occurs when the flow of water in a pipe is shut off suddenly.

water main: A large pipe that serves as a principal element of a water distribution system.

water service line: A pipe that branches off of a water main to supply water to an individual building.

watershed: An area of land defined such that a drop of rainwater falling anywhere within its boundaries eventually drains to the same outlet.

weatherhead: A fitting at which an electrical service drop enters a building.

web: The vertical element of an I-shaped structural shape or a railroad rail.

web stiffener: An element used to prevent the web of a beam or girder from buckling or failing in shear.

wedge: A simple machine that converts a longitudinal force to two large lateral forces.

weep holes: Openings at or near the bottom of a masonry wall to allow for drainage of any water that penetrates the cladding.

well: A shaft excavated from the ground surface into an aquifer for the purpose of obtaining groundwater.

well casing: A pipe inserted into an oil or natural gas well to prevent the walls of the borehole from collapsing.

wheel and axle: A simple machine that converts an applied force to a larger force through rotation.

wind turbine: A device that converts the kinetic energy in moving air into electrical power.

work: Energy transferred through the movement of a force through a distance.

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