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Understanding the Inventions That Changed the World
Course Guidebook

Professor W. Bernard Carlson
University of Virginia

Professor W. Bernard Carlson is Professor and Chair in the Department of Engineering and Society at the University of Virginia and holds a joint appointment with the Corcoran Department of History. He received his Ph.D. from the University of Pennsylvania, where he studied the History and Sociology of Science. His publications include the seven-volume Technology in World History, and he coedit a book series, Inside Technology, for MIT Press. Professor Carlson directs the Engineering Business Program at the University of Virginia and serves on the Board of Directors of the National Inventors Hall of Fame.
Professor W. Bernard Carlson is Professor and Chair in the Department of Engineering and Society at the University of Virginia and holds a joint appointment with the Corcoran Department of History. Professor Carlson joined the faculty at the University of Virginia in 1986, having taught previously at Michigan Technological University. As an undergraduate, he studied History and Physics at the College of the Holy Cross. He pursued his graduate work in the History and Sociology of Science at the University of Pennsylvania, where he received his Ph.D. in 1984. Professor Carlson subsequently studied Business History as the Harvard-Newcomen Postdoctoral Fellow at Harvard Business School. He has been a visiting professor at Stanford University, The University of Manchester, and L’École des hautes études en sciences sociales in Paris, and he has held research appointments at the Deutsches Museum in Munich and the Smithsonian Institution.

Professor Carlson is an expert on the role of innovation in American history; his research focuses on how inventors, engineers, and managers used technology to create new systems and enterprises between 1875 and 1925. His publications include *Innovation as a Social Process: Elihu Thomson and the Rise of General Electric, 1870–1900* and the seven-volume *Technology in World History*. The latter work was awarded the Sally Hacker Prize from the Society for the History of Technology in 2008 in recognition of its appeal to a broad audience. With support from the Alfred P. Sloan Foundation, Professor Carlson completed a popular biography of Nikola Tesla titled *Tesla: Inventor of the Electrical Age*, which was published in May 2013. With Wiebe Bijker and Trevor Pinch, Professor Carlson edits a book series, Inside Technology, for MIT Press; more than 50 volumes have appeared in this series.
Professor Carlson directs the Engineering Business Program at the University of Virginia and teaches a course called Engineers as Entrepreneurs. For more than a decade, he was a consultant on history and knowledge management to Corning Incorporated and has served on the governing boards of several professional groups related to history, business, and engineering, including the IEEE History Committee and the Business History Conference. He currently serves on the Board of Directors of the National Inventors Hall of Fame and as the Executive Secretary for the Society for the History of Technology.
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Understanding the Inventions
That Changed the World

Scope:

HISTORY is made not only by kings, queens, presidents, and generals, but equally by inventors and the technological powers they unleash. This course explores the inventions that have changed the world—from prehistoric times to the 21st century. Along with recounting famous inventions, such as the steam engine, airplane, atomic bomb, and computer chip, these lectures explore a number of surprising innovations, including beer, pagodas, indoor plumbing, and department stores.

The first 12 lectures investigate inventions from ancient times to 1500. The course begins with an exploration of early materials, like pottery and metals, and surveys how early inventions were used to stimulate trade, fight wars, and create empires. The middle 12 lectures look at the industrial revolution—broadly from 1700 to 1900—emphasizing how the world was transformed by new forms of transportation (railroads, canals), new energy sources (coal, steam engines, electricity), and new materials (steel, glass, plastics). The final section of the course investigates the inventions that have shaped everyday life in the 20th and 21st century, including the Model T, domestic appliances, electronics, and the Internet.

Each lecture begins with a problem or challenge that was confronting society at the time and then explains both how an invention was developed and how it worked. In the video lectures, both actual demonstrations and computer graphics are used so that you can readily understand the scientific principles behind each invention. Throughout the course, you will learn about fascinating, creative people and how they approached technology with a mixture of curiosity, determination, and passion; among the inventors you will meet are Leonardo da Vinci, Thomas Edison, Nikola Tesla, and Grace Hopper. You will also learn about how some great technologies are vernacular inventions, meaning that we don’t know who invented them, and how they were the result of numerous people over decades. Each lecture closes with a discussion of how each invention changed the world.
Through this course, you will be introduced not only to the basic principles behind many key inventions, but you will also come to appreciate how technology undergirds history, defining and shaping daily life, social structure, and how humans find meaning in the world.
This course will investigate the origins of a select number of inventions—those that fundamentally changed the course of history. Over the course of this journey, you will learn at least three things about invention: the scientific and social factors that shape an invention; the material and technological underpinnings of different cultures across history; and an appreciation of how the creative human spirit manifests itself as much in great inventions as it does in art, literature, and philosophy.

Defining “Technology”

- The term “invention” can refer to human creativity in a variety of realms. For example, we can talk about the invention of a new political system, like democracy, or a new genre of literature, like the novel. But invention in these realms is abstract and nonmaterial; the ideas are powerful, but they don’t necessarily need to be manifested in a particular way in the material world.

- What makes invention in the realm of technology interesting is that the material form does matter. An inventor can have all sorts of great ideas, but these ideas don’t change the world unless he or she comes up with a way to make them work in the world. Invention, for the purposes of this course, is all about converting ideas into things.

- In order to understand inventions, you need to inquire about the underlying scientific principles, and in order to appreciate the principles behind an invention, you have to understand how an invention works in a physical sense. But at the same time, an invention also has to work for various groups in society. Investors have to be willing to invest in it, and customers need to be willing to buy it.
Throughout this course, you will see that inventors often struggle not only to make their gizmos work in the laboratory but also to attract the interest of various groups. Inventions are as much about connecting the device with the needs, values, and wishes of the surrounding society as they are about getting the science right.

In thinking about inventions both in terms of their scientific and social content, we will ask the following questions about inventions.

- How was it invented? (What was the creative process or insight?)
- How does it work? (What is the science/engineering/practical knowledge embodied in the artifact?)
- How did it become important? (How did the invention become great, why do people have them in their lives, and what other inventions followed from it?)
- How did this invention change the world?

We are surrounded by thousands of inventions, and we could try and investigate the origins of each of these. But in this course, we will look at inventions that are “great” in four particular ways.

First, we will look at inventions that dramatically transformed daily life by making more food, energy, or information available. The steam engine and the Internet are obvious examples of this sort of great invention. While the steam engine made more power available for use in factories, the Internet has made more information accessible to millions of people.

Second, some inventions are fascinating because of the thought processes that inventors used to come up with an idea and what they had to do to develop that idea into a useful device. An example is the potter’s wheel.
Third, other inventions are technological tours de force—remarkable designs in themselves that are worthy of our attention, much as great paintings or wonderful poems are. The Japanese pagodas or the airplane of the Wright brothers would fit this category.

Fourth, there are devices that are invented in one part of the world but only really “take off” when they are transported and introduced into another culture. One great example of this is gunpowder, which was invented in China, but its real impact came when it was imported into Europe at the end of the Middle Ages. Similarly, Ted Hoff could see the great potential for putting a computer on an integrated circuit—effectively creating the first computer chip—but it took him a few years to convince his bosses at Intel that they ought to start manufacturing them.

Abundance, Order, and Meaning

To make sense of the diverse ways that people have used inventions to shape their lives and their cultures over the last 10,000 years, it is useful to think about technology as allowing people to pursue three major functions that are essential for any society to function: material abundance, social order, and cultural meaning. These three categories are broad enough that they allow us to compare inventions from different cultures without privileging one culture over another.

Humans have relied on inventions across the span of history to generate the food, wealth, and material abundance necessary to sustain the population and permit the development of a distinctive culture. To provide abundance, people have created inventions that provide food, shelter, and clothing, but also that provide new materials (ceramics, wood, and metal) used to fashion objects, new sources of power (human muscle, animals, wind, water, steam, electricity, and nuclear power), new ways to move themselves and goods (transportation), and the means to defend themselves or attack other groups (weapons).
While food, shelter, and clothing are necessary for human existence, they are not sufficient to guarantee that people will be happy or safe. Consequently, we need to consider how people rely on inventions to achieve noneconomic goals—to order society and to give life meaning.

Technology is more than just the tools humans use to provide food. In many cultures, people like to have technological artifacts—a new model of car or the latest cell phone—not just because they are practical, but also because artifacts convey messages about the person who owns or uses them. These messages can be about the individual’s gender, power, social status, values, beliefs, or emotions. Indeed, you could argue that we only know about some of these intangible qualities when they are manifested in the objects surrounding an individual.

As with individuals, so it is with societies. For example, in many cultures, we know who the rulers are by their symbols, clothes, and palaces as well as by the inventions they use to demonstrate power—through weapons, networks of roads, and monuments.

Humans possess technological artifacts for noneconomic reasons. Inventions can manifest social status, provide aesthetic pleasure, structure social interactions, and provide meaning to human existence. To consider these noneconomic functions of inventions,
it is necessary to ask a set of questions about how different cultures employ technology to create social and political order.
  o How do people use inventions to distinguish between groups (by gender and class) and confer social status?
  o What artifacts are used to guide or control the behavior of individuals or groups?
  o How does society use inventions to deploy political power—to designate leaders and followers?
  o How do leaders collect information and communicate in order to coordinate the activities of their societies?

- Across history, people have used inventions to create and maintain social and political order in a myriad of ways. In the 21st century, our interest in information technology is driven as much by a desire for social control (by collecting information about citizens and potential enemies) as it has been to improve economic productivity.

- Along with social and political order, we should also examine how different societies use inventions to create meaning—the beliefs and values that they have about themselves and their relationship to nature and the universe. We need to consider how technology interacts with the myths, religion, art, and philosophy of a culture. With regard to meaning, then, questions might include the following.
  o How do groups use inventions to illustrate and reify their worldview? How do artifacts help groups create a sense of identity?
  o How do artifacts reflect a group’s views about the place of humans in the universe? How do artifacts reflect notions of time and space?
  o What do artifacts reveal about how a group addressed and tried to resolve central puzzles or traumas?
The important thing about these three functions—abundance, order, and meaning—is that they should help us discern the different ways that various societies have developed and used inventions. While people in the West have emphasized abundance, other cultures have used technology to achieve a different mix of abundance, order, and meaning. Because of this, the inventions of non-Western cultures may look very different and even surprising to Western cultures—but that does not mean that they are inferior.

Technology versus Science; Invention versus Discovery

- While people living in the 21st century assume that new technology must spring from scientific theory, one of the surprising things that you will learn in this course is that many inventions have little or nothing to do with science and instead grow out of practical, hands-on knowledge.

- One reason for why science didn’t always precede invention is that science is a relatively new thing. The objective study of nature through observation, experiment, and measurement—what we call “science”—didn’t always exist. Indeed, science itself was invented in the 1600s, partly in response to the invention of new instruments, such as the telescope and the microscope. In fact, nearly all the inventions that came before 1600, including new metals, crossbows, and clocks, were the result of careful observation and the hands-on knowledge possessed by practical people.

- However, at the same time, we should not assume that all of the inventions after 1600 are automatically based on science. For the next 300 years (1600 to 1900), most inventions came from farmers, workers, and engineers—people who depended on the tools or machines and possessed a desire to make them work better.

- Indeed, science only really comes into the story in the early 20th century as companies needed to innovate on a regular basis to keep factories busy and, thus, hire scientists and organize research and development labs.
• What about the difference between discovery and invention? On one level, discovery is what scientists do, and invention is what inventors do. However, behind this distinction is a deeper idea about the relationship of humans and the universe.

• There are two ways of thinking about how humans interact with the material world: On the one hand, we can assume that the world is “out there,” meaning structured in certain ways and waiting to be discovered; on the other hand, we can take the view that while there is a physical world “out there,” it’s not organized, and humans provide the structure through reason and action.

• Philosophers, scientists, and engineers have spent a great deal of time deeply debating these two views. In this course we will be much more focused on invention rather than discovery—on how individuals make and shape the world.

Suggested Reading

Carlson, “Diversity and Progress.”

Nye, Technology Matters.

Questions to Consider

1. What is the difference between science and technology? Do scientific discoveries always precede technological inventions?

2. Can you provide examples of inventions that we use today that primarily provide abundance, social order, and cultural meaning?

3. While great inventions affect the course of history, do they necessarily determine history?
Pottery and metal tools represent two important great inventions in human history. Both pottery and metal tools reveal how humans around 10,000 years ago used their hands and their brains to make the final leap from being apelike to being fully human. Pottery and metal tools mark the end of the Stone Age and the start of the development of civilization. Another reason why they fit the category of great inventions is that both pottery and metal tools required significant ingenuity and, hence, illustrate the nature of technological creativity.

The Stone Age

- The Stone Age covers a really long period from 4 million B.C.E. to 10,000 B.C.E. During this period, humans (Australopithecenes) became a species separate from the apes. While the first change was bipedalism (walking upright), later changes were related to language and thought—cultural and cognitive skills.

- Bipedalism probably allowed early humans to move quickly across clearings, and they were probably better able use their arms to work or use tools. The use of more tools led to bigger brains, which led to more language use. The first tools were wood, bone, and stone. Because wood and stone tools have disappeared, we don’t know much about them. What we do know about early humans comes from the stone tools that have been discovered.

- Oldowan tools—named after the Olduvai Gorge in Africa, where some of the earliest were discovered—first appeared 2 million years ago. Stones were chipped on one side only to create a sharp edge.

- These were the only tools that Australopithecenes used for the next 1–2 million years because their physical environment was stable, so there was no need to innovate. This probably seems surprising because we assume that innovation should happen all the time.
and that change is the “normal” state of human affairs. In reality, stability is probably the more typical state of human development.

- *Homo erectus* appeared about 1 million years ago. The brain continued to grow, leading to more language, social structure, and technology, which now included baskets, fences, animal skins, and fire. Technology helped *Homo erectus* move out of Africa and into Europe and Asia.

- Eventually, *Homo erectus* began making more sophisticated stone tools known as Acheulian tools, which were two-sided tools. These were created by careful planning and the working of stone (such as flint or obsidian). This illustrates the close relationship between cognitive development and technology.

- Modern humans, *Homo sapiens*, first appeared in Africa about 70,000 years ago. They migrated to Europe, Asia, Australia, and the Americas and competed with Neanderthals and other archaic humans for resources in the environment.

- *Homo sapiens* predominated not because they had a biological advantage (they had the same brain size as Neanderthals) but because *Homo sapiens* were more effective thinkers. They were able to plan and organize better and were able to adapt to the changing environment (ice age). They were also capable of symbolic thought; there are cave paintings from 25,000 years ago. Humans used pictures (representations) to make sense of their environment.

- By 10,000 B.C.E., then, human groups around the world were living in small kinship groups, hunting and gathering, living nomadic lives (following game or going to more plentiful places), and experimenting with planting seeds to grow vegetables and grains. They possessed some sort of myth, religion, or meaning.

- Nevertheless, humans were dependent on the vicissitudes of nature. If a drought drove off the game or ruined early farming efforts, then people would die. All groups were at the subsistence level, so to
permit a shift to abundance, there were new techniques for growing and processing food, and there was the development of a new level of technology created by using human ingenuity—the great inventions of pottery and metal tools.

The Development of Pottery

- Clay occurs all over the world and will become hard and brittle when heated by the Sun or a hot fire. Because it was widely available, the development of pottery was probably a simultaneous invention, discovered separately by different groups around the world. Not all great inventions have a single inventor.

- The craft of pottery involves three activities: The clay has to be mixed with water until it is soft enough to work but still stiff enough to be shaped, then the clay needs to be shaped into a vessel or other form, and finally, the vessel must be fired to convert it from a plastic to a rigid condition. The first examples of clay objects that we have are not actually pots but, rather, figurines.

- The oldest pots that have been discovered date from 18,000 to 16,000 B.C.E. and come from a cave in China. Equally old pots from 12,000 B.C.E. have been found in Japan. Archaeologists believe that the first pots were made in order to store food. There is some evidence that people first attempted to carve stone containers to store food, but this is nearly impossible to do using only stone tools. Instead, they began making containers out of “artificial” stone, or clay. They may have come to this idea by first coating baskets with clay.

- The first pots were made by hand, probably by making long ribbons of clay by rubbing the clay together in one’s hands. This technique was probably borrowed from an early textile technique whereby thread or yarn was made by rubbing fibers together. The long ribbons were then coiled on top of one another to form a vessel—perhaps this technique was borrowed from basketmaking.
Once the vessel had been made out of the coiled ribbons of clay, the potter would smooth out the surfaces, both inside and outside. One of the surprising things in looking at the oldest pots in museums is how symmetrical they are. How did they get them to be nearly circular?

In working on a vessel, the potter would have either had to move his hands around the pot or physically move himself around the pot. At some point, potters realized that they could move the pot instead of themselves by placing the pot on a flat surface that could be turned on a pivot—what we would call a turntable.

Before long, potters realized that it was advantageous to have the turntable spin continuously, kept in motion by pulling it periodically with their hands or kicking it with their foot. Now, the energy needed to shape the pot came not from their hands but from the momentum of the spinning wheel. The first potter’s wheels appeared in Mesopotamia around 8000 B.C.E., and with them, potters were able to make elegant, symmetrical designs.

The potter’s wheel is important because it is one of the first machines created by humans. The potter’s wheel is a cunning device because the wheel allowed the potter to apply more energy to the task of making pots by storing energy via the momentum of the wheel—that is, the wheel would have a tendency to keep spinning once it had started.

Pottery can be dried in the Sun or even in a cooking fire, but to make it really strong, you need to heat it or fire it in the range of 850–1,300°F (450–700°C). It then needs to be cooled down slowly to prevent cracking. They eventually created special ovens, or kilns, in which the pots were stacked inside, a fire was built underneath, and a bellows was used to stoke the fire. Kilns date from the 4th millennium B.C.E. While the first fuel was wood, early potters soon discovered that charcoal burned hotter and longer.

Like all inventions, pottery had a number of spinoffs. These follow-up inventions didn’t come as fast as they do today, but within a few
centuries of making pots using the potter’s wheel and kilns, potters were creating glass objects and even wheeled vehicles.

The Development of Metals

- The most important child of pottery was the development of metals. The ability to use different metals is a central story in the history of technology, and archaeologists and historians have tended to “catalog” and even “rate” cultures by what metals they had at their disposal.

- Since the Greek poet Hesiod in the 8th century B.C.E., historians have spoken of a Copper Age, Bronze Age, and Iron Age. However, we shouldn’t take this progression of ages too literally because various societies mixed and matched the metals they used at different times. In the ancient world, people knew about gold, silver, copper, tin, iron, lead, and mercury. Copper and bronze are the two metals that had the biggest impact, and they tell us a great deal about the nature of human ingenuity at the dawn of civilization.

- Some metals, fortunately, occur in a pure state in nature; that is, they can be found in rocks and immediately shaped or hammered into tools or jewelry.
  - Native Americans in Michigan and Canada found large pieces of pure metallic copper, which they shaped into ingots or objects which in turn were traded all over North America.
  
  - In ancient Europe, people discovered that bits of meteorites were made of iron and could also be hammered into objects; indeed, the earliest word in Greek for iron is *sideros*, meaning “from the stars.”

  - Early humans found gold nuggets in streams and riverbeds; early on, they regarded gold as a “noble” and valuable metal because of its reluctance to interact chemically (and, hence, it’s difficult to dilute its value).
Evolution of Man

4 million years ago

1 Australopithecine
East Africa
Bipedal

2 million years ago

2 Homo Habilis
East Africa
Oldowan tools

3 Later
Australopithecine
East Africa
bigger jaw
(died out 200,000 years ago)

1 million years ago

4 Homo Erectus
Eurasia
Acheulian tools
Fire

5 Neanderthals and other Archaic humans
(died out 200,000 years ago)

70,000 years ago

6 Homo Sapiens
E. Africa then
Eurasia, Australia, N. America
Symbolic thinking

15,000 years ago

7 Mesolithic hunting and gathering groups
• Other than copper, iron, and gold, metals are almost always found mixed up chemically with other substances in rocks known as ores. Hence, the challenge for the first metallurgists, or smiths, was to figure out how to use some combination of heat, chemistry, and hammering to convert the ore into a pure metal. The story of how early smiths did this is another great example of the ingenuity of early humans.

Suggested Reading

Cooper, *Ten Thousand Years of Pottery*.

Raymond, *Out of the Fiery Furnace*.

Questions to Consider

1. What is the broader significance that some of the first inventions by humans were things like paintings, flutes, and statues, as opposed to pots and tools?

2. Why is the potter’s wheel an ingenious machine?

3. Even though bronze required finding and mixing two ores—copper and tin—why was it worth the extra trouble?
Not only are beer, wine, and distilled spirits something we still enjoy, they are also great examples of people learning how to deliberately manipulate chemical and biological processes in order to get a particular outcome—i.e., an alcoholic beverage. In this lecture, you will learn that people have been deliberately manipulating these organic processes for thousands of years, beginning even before the civilizations of ancient Mesopotamia and Egypt. Beer, wine, and liquor are great inventions that remind us how humans use things to shape social order and convey cultural meanings and that technology is not just about the inorganic but also the organic.

**Beer**

- Beer is made out of barley (a grain), hops (which provide the yeast for fermentation), and water. Wine, of course, is made from grapes. The agricultural revolution is the historical period during which people come to have the grain and grapes needed for these drinks.

- The agricultural revolution was a shift in human societies from a subsistence economy to one capable of producing abundance. It involved domesticating wild plants and animals and converting them into crops and livestock.

- The dates of the agricultural revolution range from 8500 B.C.E. for the Fertile Crescent to 3500 B.C.E. in Central America. Over the course of centuries, people in the Fertile Crescent and elsewhere figured out how to grow lots of grain, vegetables, and fruits. The challenge then became how to preserve this bountiful harvest for the winter months and as a reserve against famine.

- Beer is one of the oldest beverages humans have produced, dating back to at least 5000 B.C.E., and it is mentioned in the earliest written records of ancient Egypt and Mesopotamia. One of the
ways that early humans cooked grain was to boil it in some water; if it was nice and thick, it would be a porridge, and if it was thin, it would be gruel.

- Fortunately, grains like wheat and barley have two almost magical characteristics. First, if you soak the grain in water and let it start to sprout, it starts to taste sweet. This happens because the moistened grains release diastatic enzymes, which convert the starch in the grain into maltose sugar or malt. Given that humans have taste buds for sweetness and that there weren’t that many sweet-tasting things, people must have really liked this malted grain. In response, they developed deliberate techniques for soaking and drying the grain, to malt it. Because barley gives off the most maltose sugar, they focused on that grain.

- Second, if they let a gruel of malted barley sit around for a few days, they found that it became slightly fizzy and pleasantly intoxicating, the result of wild yeasts in the air causing the sugar in the gruel to ferment and become alcohol. Based on these two characteristics, beer was born.

- Early brewers realized that if you boiled the gruel, additional enzymes were activated at the higher temperature, and more of the sugar in the malted grain was released, thus providing more sugar to be converted into alcohol.

- By choosing the grain; adjusting how long you boiled the brew and let it sit; and adding honey, fruits, and nuts for flavoring, brewers...
came up with all sorts of different kinds of beer. It wasn’t until the Middle Ages in Europe that brewers began adding yeast derived from the hops plant.

- Because almost any cereal containing certain sugars can undergo spontaneous fermentation due to wild yeasts in the air, it is not surprising that beer-like beverages were independently developed by different groups around the world.

- The main advantage of beer was that it provided a tasty way for people to consume the calories available in the large amounts of grain produced by the agricultural revolution. In ancient Egypt, crops were converted into both bread and beer, so the average Egyptian diet was largely a combination of both items.

- To preserve barley for use in times of famine, the Mesopotamians not only stored grain in government warehouses, but they also baked sprouted barley into hard cakes called *bappir*, which would keep for years and could be crumbled, mixed with water, and used to make beer. Like other alcoholic beverages, beer had an important health advantage in that the alcohol kills dangerous bacteria, so beer was safer to drink than ordinary water.

- Much like today, beer was consumed by ancient peoples as a social beverage. It was the drink for every man. Indeed, beer was so important to Mesopotamian and Egyptian cultures that it was regarded as a gift from the gods and was present in many myths and stories.

- Overall, beer was an invention that changed history by providing a means for preserving the calories in staple crops so that they could be consumed at a later time. In doing so, beer played a role in sustaining a larger population in agriculturally based societies as opposed to hunting-and-gathering communities.
Wine

- Because wine involves a different ingredient for fermentation—grapes instead of grain—we shouldn’t be surprised that its history is different than that of beer. In particular, from almost the beginning, wine was not just a beverage but a means by which people made political or social statements. Wine is also a great invention because it shows us how the economies of the Middle East and the Mediterranean evolved in the 1st millennium B.C.E.

- Wine is simply the fermented juice of crushed grapes. Natural yeasts in the grape skins cause the sugars in the juice to become alcohol. Like beer, wine was safer to drink than water, and winemaking was also a way of preserving fruit.

- It is plausible that early hunting-and-gathering groups made wine from wild fruit, including grapes, but because wild grapes are small and sour, additional innovations were necessary, such as carefully finding and breeding a better grape (Vitis vinifera) for making wine, figuring out how to add yeast and additional sugars to aid the fermentation process, and having pottery jars in which the wine could ferment and be stored.

- The earliest wine grapes are believed to have originated in modern-day Georgia (located south of Russia) and then spread across the Middle East. Winemaking dates back to at least 5400 B.C.E., based on the discovery of a reddish residue at the bottom of fermentation jars found in the Zagros Mountains, in what is today Armenia and northern Iran. From the Zagros Mountains, knowledge of how to make wine spread west to Greece and Turkey and south to Syria, Lebanon, and Israel, and then to Egypt.

- Initially, grapevines were grown intertwined with fig and olive trees, alongside fields of barley and wheat. Because few grapes were grown and winemaking is a finicky process, wine was expensive and was reserved as a luxury drink for the rich and powerful.
While wine became fashionable and available in Mesopotamia, transportation kept costs high and limited consumption to the rich.

- Although high transportation costs limited the production and distribution of wine in Mesopotamia, it was a different story in the societies taking shape around the eastern Mediterranean. By taking advantage of the fact that it cost less to move goods on a ship at sea than over land in an oxcart, several societies—such as the Greeks—developed wine into a major product.

- As Greek merchants and sailors improved their ships, or galleys, they were able to reach more ports and larger markets. Greek winemakers (vintners) made improvements to production, including planting vines in neat rows and on trellises to ease pruning and harvesting (which also fit more vines into less space), modifying the wine press to get more juice, working to create distinctive wines from their region and vineyard (early product differentiation and even “branding”), and perfecting clay *amphorae* for shipping vast quantities of wine all over the Mediterranean.

- While Greek farmers initially grew grain, olives, and grapes, demand for wine in Greek cities and elsewhere in the Mediterranean prompted them to focus exclusively on wine production with the result that some city-states (e.g., Attica) had to import grain to feed vineyard workers. Making this shift from subsistence to commercial farming was highly appealing because, by one estimate, farmers could earn up to 20 times more by cultivating vines as opposed to growing grain.

- By the 6th century B.C.E., wine production had become so important in the city-state of Athens that property-owning citizens were classified according to their vineyard holdings. More than just being central to the economic underpinning of ancient Greece, wine played additional important roles in Greek life, including that it represented civilization.
Spirits

- The story of alcoholic beverages—such as brandy, vodka, or gin—grows out of beer and wine but requires us to jump nearly 1,500 years in time from the Greeks to Spain in the 8th century. Spirits are alcoholic beverages that contain ethanol. The ethanol is produced by fermenting fruit or grain, and then the alcohol is concentrated by using a chemical process known as distillation.

- Distillation is a method for separating liquid mixtures by taking advantage of the fact that different liquids can have different boiling points. As one heats a mixed liquid, the fluids with a lower boiling point will vaporize sooner and can be captured with the appropriately designed container. Because alcohol boils at 78°C and water at 100°C, it’s possible to slowly heat a mixture of alcohol and water and draw off the alcohol first.

- Because even the hardiest yeasts used to ferment wine cannot survive in an alcohol-rich environment, the upper limit for the alcohol content of wine is about 15 percent. Rectification allowed distillers to overcome this limit and create really strong drinks. Today, the alcohol content of liquor is denoted by proof, and an 80-proof gin is 40 percent alcohol by volume, and 150-proof rum would be 75 percent alcohol.

- Consumption of distilled drinks rose dramatically in Europe in the mid-14th century, when they were commonly used as remedies for the Black Death. In northern Europe, where wine was scarce, people learned to distill the barley mash normally used to brew beer. Elsewhere, local people continued to distill wine, which in German was called branntwein and in English “brandywine,” which subsequently came to be shortened to “brandy.”

- Europeans continued to experiment with distillation, often taking advantage of surplus crops. Taking place during the early modern era, when new nation-states were taking form, many of these new beverages came to be associated with particular nationalities: gin
(England), schnapps (Germany), grappa (Italy), *akavit* (Scandinavia), and vodka (Russia).

### Suggested Reading

Al-Hassani, et al., *1001 Inventions*.

Diamond, *Guns, Germs, and Steel*.


Smith, *The Emergence of Agriculture*.


### Questions to Consider

1. Why is beer an important component of the agricultural revolution that led to the development of the first civilizations?

2. What are some of the ways that the Greeks made wine seem more socially prestigious than beer?

3. What role did alchemy play in the development of alcoholic beverages?
The Galley, Coins, and the Alphabet
Lecture 4

Inventions are used not only to increase quantity and quality but also to facilitate the economic, social, and intellectual interaction of groups of people. Collectively, engineers and economists refer to the technology used to move resources, goods, people, or information as infrastructure. In this lecture, you will learn about the first inventions that revolutionized the infrastructure of the ancient world—namely, ships (or galleys), coins, and the alphabet. These infrastructure inventions allowed trade to flourish in the ancient Mediterranean and ideas to spread.

The Origin of Ships and Trade

- We don’t really know how boats and ships were invented, because they date back tens of thousands of years. It’s clear that ancient peoples migrated to various places—from Southeast Asia to Australia—by using boats or rafts, but we have no idea what kind of vessels they created to make these oceangoing trips. All we know is that ancient people somehow crossed 50 to 60 miles by sea to get there.

- From an archaeological standpoint, the earliest boats that have been found are dugouts, dating from about 8000 B.C.E. and discovered in prehistoric Holland and Scotland. Dugouts were made by hollowing out a large log.

- People in the Pacific developed their own dugouts and improved the stability by adding outriggers. Equipped with sails and paddles, people in the Pacific used these boats to populate islands from New Zealand to Hawaii (well over a third of the surface of the world).

- Canoes (based on prehistoric boats built by Native Americans) easily tip over because they lack a keel along the bottom of the hull. The weight of the keel adds stability to the hull as well as strength. The origin of the keel is another part of the story of the evolution
of ships that seems to be a complete mystery. Egyptian boats don’t have one, but Phoenician and Greek ships do.

- Some maritime experts conjecture that the keel evolved from dugouts and that the keel represents a blending of several boatbuilding traditions. The keel is probably also the result of the confluence of two other factors: economic, in the sense that the societies in Near East were moving away from “state economies” to economies built on trade; and environmental, in that ships were shaped to suit the new environment of sailing on the Mediterranean as opposed to rivers like the Nile.

- In other words, as one ventures farther out into the Mediterranean, away from the rivers and the coast, it would become very important to have a stable ship, lest you lose your valuable cargo by capsizing in a storm—and a keel is essential for stability at sea.

- In the river-valley civilizations of Mesopotamia and Egypt, the agriculture surplus was grown by peasants but controlled and distributed by the king and bureaucrats. Moreover, the king also controlled trade between his state and other nations. However, in the ancient Mediterranean circa 1800 to 1500 B.C.E., the dominance of the Egyptian rulers was disrupted by the invasion of several groups from the north.

- Over the next five centuries or so, different cultures in the eastern Mediterranean established themselves, relying on unique resources and skills that they traded with other groups. Some examples include the Greeks, who specialized in olive oil and wine (which were shipped easily in amphora); the Minoans on Crete, who had obsidian for making sharp tools; and the Phoenicians, who had purple dye (made from rotting snails found in their homeland of modern-day Lebanon) and Lebanese cedar.

- To facilitate this trade, ancient boatbuilders from all of these groups gradually shaped wooden ships generally known as galleys, which were designed to suit the conditions of the Mediterranean. These
ships were generally longer and narrower (i.e., the beam) than the ships developed centuries later by Europeans for sailing in the Baltic Sea or the Atlantic Ocean.

- While the earliest galleys were initially of shallow draft and could be pulled up on the beach, the growth of trade prompted Greeks to build progressively larger vessels. They referred to particularly large freighters as *myrioph*, meaning “ten thousands,” because these ships carry up to 10,000 amphorae.

- Bigger ships, though, meant building ports where the ships could either anchor safely inside a harbor or come up to a dock. A great deal of Greek and later Roman civil engineering was devoted to creating piers, quays, and artificial harbors behind masonry jetties. To build this port infrastructure, Roman engineers perfected hydraulic cement, which, when set, could be submerged under water.

**Coins**

- While the ancient world relied on galleys to move goods and people, the growth of trade also depended on developing a few related practices—the invention of currency and the alphabet—and these, too, were carried across the then-known world by galleys.

- For thousands of years, economic transactions were essentially barter. If you had some pots that someone else wanted, and the other person possessed some pigs that you liked, then you would trade with each other, haggling over how many pots a pig was worth. However, suppose that you wanted to buy one of the other person’s pigs but that he or she didn’t want your pots. How, then, might the two deal? The solution is that the two parties need an intermediary good that they both agree has value. That’s what currency is.

- Because metals such as gold, silver, and copper were relatively rare in ancient civilizations and didn’t lose value, they seemed to be good candidates to serve as intermediary goods. By 2500 B.C.E., Egyptian merchants were conducting transactions by using standard-sized copper rings. By 2000 B.C.E., rulers in Cappadocia
in central Turkey issued the first “state” currency in the form of silver ingots.

- Greek historian Herodotus tells us that coins in 687 B.C.E. were introduced by the Lydians, another group in ancient Turkey. Lydian coins were made out of electrum, a naturally occurring compound of gold and silver. Coins proved popular with traders because they were easy to carry and could always be melted down for the metal they contained.

- People, of course, quickly figured out that you could shave off a small amount of the metal and trade that separately. To prevent shaving, the Greeks and Romans added a raised ridge to the edge of their coins so that any tampering would be immediately apparent.

- As another form of infrastructure, coins greatly facilitated trade between different societies not only around the Mediterranean, but even farther afield. Large hoards of silver Roman coins have been found in archaeological digs as far away as northern India.

The Alphabet

- Although we don’t necessarily think of it as a technology per se, the alphabet is an important nontangible piece of infrastructure. Just as the galley allowed people and goods to move from one place to another, the alphabet—a common set of symbols representing sounds—plays an important role in moving ideas from one person to another.
• The Sumerians developed the first writing system, cuneiform, to keep track of tax transactions between the subjects and the king or temple. Cuneiform was a pictographic system with little pictures being scratched on the surface of soft clay tablets. Over time, these little pictures became more abstract, probably as bureaucrats rushed to get through recording the large number of transactions and because only they needed to read the records.

• Egyptians had a similar pictographic system, called hieroglyphics. Most people are familiar with the hieroglyphics that were carved into stone monuments and tombs, with the symbols realistically representing the idea or object. People are probably less familiar with the fact that by the 3rd century B.C.E., Egyptian scribes developed a more abstract form of hieroglyphics—called demotic hieroglyphics—that was better suited for writing quickly using ink and papyrus.

• While it is feasible to create a pictographic writing system under the authoritarian rule of an empire, the emperor can insist that everyone use the same symbols to mean the same thing, so an empire is not necessarily the best place to experiment with creating new writing systems. Instead, the next new writing system turned up in the political and geographic space between the Egyptian and Mesopotamian empires—namely, the Levant (which today is Israel, Lebanon, and Syria).

• For many years, scholars believed that the first alphabetic scripts could be traced to around 1600 to 1500 B.C.E., to the Phoenicians, a trading society based on the coast of today’s Lebanon and Israel, and that the Phoenicians were not particularly influenced by, for example, Egyptian hieroglyphics.

• However, a discovery in 1999 of two inscriptions (graffiti) in Wadi el-Hol, Egypt, changes that view. Written in what seems to be a hybrid of demotic hieroglyphics and a proto-alphabet, these inscriptions were produced by the Semitic-speaking people then
living in Egypt. Based on this finding, scholars now push back the origin of the alphabet to between 1900 and 1800 B.C.E.

- The transition from a pictographic to a phonetic (sound-based) system seems to have taken two steps, one borrowing from cuneiform and the other from hieroglyphics. Writers first reduced the number of abstract symbols in the system. For example, the Ugaritic script used during the 14th century B.C.E. in what is today modern-day Syria employed 30 simplified cuneiform signs.

- At the same time, another alphabetic system emerged that was influenced by hieroglyphs. Called the proto-Sinaitic alphabet, it consisted of pictographs, but each pictograph represents a sound of a consonant rather than a thing or idea. Hebrew is a modern direct descendant of the proto-Sinaitic alphabet because it doesn’t have any letters for vowels. It was the Phoenicians who pulled these two steps together to create the modern alphabet, where a limited set of symbols (letters) are used to represent the sound of words.

**Suggested Reading**

Davies, *A History of Money*.

Gardiner, ed., *Conway’s History of the Ship*.


**Questions to Consider**

1. What is meant by “infrastructure,” and why is it important for the history of civilization?

2. How did the physical environment of the Mediterranean Sea shape the form of the Greek galley?

3. What do linguists think the Phoenicians did to older pictograph systems (like hieroglyphics) in order to invent the modern alphabet?
Using the crossbow as the central example, this lecture will examine several major ideas. First, creating a stable society is not easy; it took three dynasties 1,200 years to achieve. In addition, because the crossbow was in the hands of many groups during the Warring States period, it contributed to ongoing instability and may have shaped a portion of the philosophy put forward by Confucius. Finally, the first emperor, Shihuangdi, achieved his position by skillfully using the crossbow in battle and then deploying technology to manifest his power.

**Ancient Chinese Dynasties**

- Like Mesopotamia and Egypt, Chinese civilization grew up around two major rivers that permitted the development of agriculture circa 7500 B.C.E. The Yellow and Yangtze rivers have floods that can wipe out fields; therefore, flood control was needed to channel rivers and protect fields, so intensive irrigation was developed to direct water to as many fields as possible. This allowed the development of two staple crops: millet (a grain) in the north and rice in south.

- While Chinese mythology talks about several early dynasties, the first dynasty for which we have archaeological and written evidence is the Shang dynasty (~1600–1030 B.C.E.). By this time, Chinese society consisted of a network of walled towns. The king gained power by defending towns from nomadic invaders and by integrating a variety of religious functions and serving as high priest.

- Consequently, the king was constantly on the move to defend towns and impose authority. There was no bureaucracy; the king relied on extended family. Guided by divination from oracle bones, the Chinese system of writing developed as priests sought to capture the divine messages of the bones.
The Zhou (~1030–771 B.C.E.) were invaders from Central Asia who defeated the Shang. To justify the overthrow, Zhou leaders introduced the political concept known as the “mandate of heaven,” which postulates that heaven blesses the authority of a just ruler but would be displeased with a despotic ruler and would withdraw its mandate, leading to the overthrow of that ruler. The mandate of heaven would then transfer to those who would rule best.

To manage the territory, the Zhou king gave loyal sons and allies fiefdoms to rule, and each fiefdom was expected to supply soldiers to the Zhou king. This political system worked while Zhou kings were able to expand, conquer more territory, and create more fiefdoms, but when expansion stopped, the dynasty lost credibility, and individual nobles began exercising more power.

This led to what is known as the Warring States period (~475–221 B.C.E.), during which the Zhou kingdom disintegrated into hundreds of warring city-states and then eventually consolidated into seven regional powers (Warring States). Competition between the states stimulated innovation: Each state built defensive walls, there was a rapid development of iron for armor and weapons, and huge armies were deployed (up to 100,000 men).

Dynasties in Chinese History

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Event</th>
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<tbody>
<tr>
<td>~7500 B.C.E.</td>
<td>cultivation of millet and rice</td>
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<tr>
<td>~1600–1030 B.C.E.</td>
<td>Shang dynasty</td>
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<tr>
<td>~1030–771 B.C.E.</td>
<td>Zhou dynasty</td>
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<tr>
<td>~475–221 B.C.E.</td>
<td>Warring States period</td>
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<tr>
<td>221 B.C.E.</td>
<td>Shihuangdi becomes first emperor; establishes Qin dynasty</td>
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<tr>
<td>202 B.C.E.–220 C.E.</td>
<td>Han dynasty</td>
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To mobilize huge armies, states became highly organized, with bureaucrats tracking households and agricultural output and then collecting taxes. The great philosopher Confucius (551–479 B.C.E.) wrote just as the Zhou dynasty was disintegrating.

The Crossbow

During the Warring States period, one particular weapon, the crossbow, came to have significant impact on the course of events. The crossbow is a weapon consisting of a bow mounted on a wooden stock that shoots projectiles, which look like short arrows but are called bolts. It includes a trigger mechanism for releasing the bowstring.

The bow and arrow dates back to the middle Stone Age (11,000–9000 B.C.E.). The power of the bow comes from the archer using his arms to pull back on the string and bending the bow. A crossbow is an improvement on the bow in that the archer puts the bow under his foot and uses muscles in his legs and back to draw the bow back.

This means that a crossbow is able to store more energy and, hence, fire the bolt with a greater velocity than an ordinary bow. Delivered with more force, a crossbow bolt did much more damage when it hit any enemy soldier or target.

Tribal groups throughout much of China and Indochina hunt with crossbows, but it’s not clear whether the tribal groups invented the crossbow or picked it up from the Chinese. However, what seems clear is that during the Zhou era, the crossbow was very useful in fighting various horse-mounted invaders who came from the West. The Chinese seemed to have called all of these barbarians “Huns.”

The earliest handheld crossbows with bronze triggers that have been found date from the 6th century B.C.E. and come from the excavation of tombs in Qufu, Shandong, capital of the state of Lu, one of the Warring States. These bronze-trigger mechanisms are remarkable because dozens of samples have been found in archaeological excavations.
• Most consist of an ingenious mechanism consisting of three moving parts on two axles inside a case. As the trigger is pulled back, it causes a U-shaped pivoted arm to come down. This U-shaped arm catches a second pivoted arm that has a notch for the bowstring. When the second arm dips into the case, the bowstring is released.

• This mechanism was designed so that it was able to store a large amount of energy when the bow was drawn but was easily fired with little recoil when the trigger was pulled, thus allowing for precision shooting. Remarkably, unlike later trigger mechanisms in guns, this design doesn’t require any sort of spring.

• Notably, by the Warring States period, the parts in this trigger mechanism were standardized and produced in huge quantities. Some historians view this trigger mechanism as the first example of a machine with interchangeable parts, a development that was generally regarded as one of the great achievements of the industrial revolution of the 19th century—but here we have ancient Chinese making devices with standardized parts 2,000 years earlier.

• Standardized parts not only meant that armies could have huge companies of crossbowmen, but because it was relatively easy to disassemble the mechanism, the weapons could be quickly repaired on the battlefield. As simple as the mechanism may seem, the Chinese took great satisfaction in that

When using a crossbow, the archer puts the bow under his foot and uses the muscles of his legs to draw back the bow and position it.
even when the Huns got ahold of one of their crossbows, they could never figure out how to duplicate the trigger mechanism.

- Though it’s hard to say for sure, the crossbow was a highly appealing weapon to ambitious warlords in the Warring States period. As a result, the nature of warfare changed dramatically, from fielding armies of perhaps 40,000 soldiers to having armies of over 100,000 troops clashing.

- There is, however, a downside to arming ordinary soldiers with a weapon as powerful as a crossbow. The first problem was that during the Warring States period, soldiers and ordinary people assassinated any number of members of the ruling class. The second problem was that well-armed troops could switch allegiances at any time and align themselves with a different warlord. In response, warlords were often cruel and despotic, but the overuse of such practices could lead to assassination and rebellion.

Confucian Political Thought

- The great Chinese philosopher Confucius (551–479 B.C.E.) lived and wrote during the time that the Zhou dynasty was falling apart. During the Warring State period, his disciples refined his political ideas in response to what they saw going around them.

- In particular, Confucius and his disciples called for the restoration of the mandate of heaven. Together, they looked nostalgically upon earlier days and urged those with political power to model themselves on earlier examples of wise and fair rulers and not to rule by coercion and bribery. Instead, they believed that if a ruler were to lead correctly, by action, that orders would be deemed unnecessary—that the subjects would simply be inspired to imitate the proper actions of their ruler.

- For Confucius, relationships, especially reciprocal relationships, were everything. The people had to respect the ruler, but the ruler had to respect the people. To gain their respect, the ruler had to
inspire the people; he had to give them reasons to persuade them to follow him.

- The great scholar of the history of Chinese science, Joseph Needham, suspected that in light of the fact that the crossbow had tipped the balance of power away from the warlords and to the people and that coercion wasn’t working, then it became likely that the disciples of Confucius would argue for a politics based on respect and persuasion. For Needham, the crossbow was not only a marvel of early mechanical engineering, but also a great invention that shaped the evolution of Confucian philosophy.

- It would, however, take another dynasty—the Qin dynasty (221–202 B.C.E.)—before the ideas of Confucius could take hold in China and guide how the Han emperors ruled. Shihuangdi (259–210 B.C.E.) became the first emperor by defeating all Warring States. He was victorious in battle by using crossbows.

- Once he became emperor, Shihuangdi took a number of steps to consolidate his power, including confiscating all weapons and tearing down individual walls, standardizing laws and language, and standardizing coins.

- Remarkably, he also started using technology in new ways to demonstrate, or reify, his authority. He started the Great Wall of China in the west, developed a road system, built canals, and established a uniform system of weights and measures. With Shihuangdi, we see for the first time how political leaders often use technology to advance their agendas.

- The Qin dynasty, however, didn’t last. Shihuangdi and his son spent too much time fighting wars in the south. He rejected Confucianism, killed scholars, and burned books; hence, there was no mandate of heaven to justify his rule.

- As a result, the Qin dynasty ended after just two emperors and was replaced by the Han dynasty (202 B.C.E.–220 C.E.). To justify their
coming to power, the Han brought back Confucianism and fully established the mandate of heaven.

**Suggested Reading**

Needham, et al., *Science and Civilisation in China*.


**Questions to Consider**

1. Why was the crossbow superior to the bow and arrow that preceded it?

2. How did the political and military conditions of the Warring States period influence the design and use of the crossbow, and vice versa?

3. The crossbow unexpectedly placed more power literally in the hands of ordinary soldiers and people. Can you think of other examples of inventions that did the same, and what were the political repercussions?
Invention can be shaped by political change; as groups or leaders vie for power, they appropriate and create the technology they need to get ahead. Rather than appropriating inventions that would allow them to exercise brute force, the Romans took up technology—large-scale works of civil engineering to demonstrate a political ideal, that of a commonwealth. To show you how Roman inventions reflected the idea of commonwealth, this lecture focuses on two examples: their system of aqueducts and the Colosseum in Rome.

The Arch: The Secret of Roman Engineering

- The arch was the essential invention at the heart of nearly all major Roman structures. Before the arch, most early buildings were built using post-and-lintel construction. Buildings such as Stonehenge in England and the Parthenon in ancient Athens were created by laying a flat beam or slab (the lintel) across the top of two columns or posts.

- Due to the weight of the lintel, the posts had to be fairly close together; if they were too far apart, the lintel would snap. This limitation meant that a grand building like the Parthenon needed to have lots and lots of columns.

- Roman engineers overcame the limitations of the post-and-lintel system by perfecting the arch. To make an arch, builders first constructed a curved wooden scaffolding between two pillars. They then built up the arch by placing wedge-shaped stones (known as voussoirs) along the curve of the scaffold. In the center and at the top, they positioned a heavier block, known as the keystone. The downward thrust (weight) of the keystone, and of the building above it, was transferred through the arch to the supporting pillars on either side, compressing and locking the other stones into place. Once the scaffolding was removed, the arch would stay in place for centuries.
While it was traditionally believed that the Romans invented the arch, it now appears that the Babylonians and ancient Persians knew about the arch, but they tended to use it only for underground constructions. The Romans, however, realized that the arch could be used above ground, and they employed it in a variety of creative ways. For instance, for bridges or viaducts that could span valleys, the Romans not only created a long string of arches but also stacked them on top of one another.

Along with being strung together end to end to create a bridge, arches could be placed side by side to create a curved roof or vault. In addition, the form of an arch could be turned through 360 degrees so that it spanned a complete circle to create a dome.

Roman buildings are generally made up of a combination of arches, vaults, and domes. Using these three elements, Roman engineering created many of the finest structures in history, and the arch is the secret behind it all.

Commonwealth and Invention

Historians sometimes criticize the Romans for not inventing many new technological devices, but their genius lay in shaping technology that suited their political situation, and consequently, they focused on inventions that advanced commonwealth and spectacle.

From the beginning of the Republic through to the Empire, the senators and emperor were faced with an ongoing challenge to justify their authority. To answer questions of power, Romans invoked the idea of a commonwealth.

The Roman state represented all classes of Roman society—an ideal embodied in the four initials displayed on the standards of the Roman army: SPQR (senatus populusque Romanis: “the Senate and people of Rome”).

The Roman Republic was a commonwealth; its purpose was to safeguard the common well-being of the Roman people. And
to realize this vision of a commonwealth, to make sure that they retained the support of the people who voted them into political office, Roman aristocrats frequently sponsored public works.

- Once they came to power, the emperors embraced this tradition of sponsoring public works. Augustus justifiably claimed to have transformed Rome from a city of brick to one of marble. He carried out a vast program of public building, including the construction of a new Forum, the grand square that was at the heart of the city of Rome.

- His successors in the 1st and 2nd centuries C.E. were able to draw on the vast resources of the Roman state to order the construction of new cities and harbors, roads and aqueducts, elaborate public monuments, baths, and amphitheaters.

- By far, the most impressive and famous example of Roman engineering for the commonwealth were the aqueducts built to supply fresh water to Rome and other cities in the empire. As the Roman Republic conquered more territory and patricians used their wealth to buy up land, peasants were forced off the land and moved to Rome, swelling the population to a million people.

- To provide fresh water for this huge population, the Senate ordered the building of the first aqueduct, the Aqua Appia, in 312 B.C.E. Over the next five centuries, Roman authorities created 10 additional aqueducts—a system of over 300 miles (475 km) of stone channels and pipes—to provide water for their capital city.

- Although we associate aqueducts with the impressive arched stone bridges that carried water across valleys, an aqueduct was actually a much more complex system in which these bridges, or viaducts, were only one component.

- For the Romans, an aqueduct was a system comprised of reservoirs, stone water channels, tunnels, pipes, and fountains that gathered and carried water from mountain springs to the heart of their cities.
Aqueducts were carefully designed so that the water flowed continually downhill at a gentle gradient. To achieve a consistent gradient over dozens of miles of changing landscape required Roman engineers to become both master surveyors and great planners.

**Spectacle and the Colosseum of Rome**

- Along with investing in civil engineering works such as aqueducts, the emperor and the patricians spent their surplus wealth on spectacles—elaborate religious festivals, sporting events, and parades. As popular events, these activities required large public venues, and Roman engineers devoted much effort to designing amphitheaters and stadiums with various innovations.

- Of these venues, the greatest was the Colosseum in Rome. Built at the request of emperor Vespasian, the Colosseum took 10 years (70–80 C.E.) to build. When finished, it was the largest structure of its kind—615 feet long, 510 feet wide, and 159 feet tall. What survives today is only about one-third of the original structure.

Despite Christian tradition, there is no indication that early martyrs were executed in the Colosseum for their faith.
• Built on land reclaimed from a swamp, the Colosseum has a foundation that goes down 40 feet, consisting of a concrete platform and travertine piers. Using a combination of hundreds of arches and vaults, Roman engineers created a four-level stadium that could hold 45,000–50,000 spectators. Eighty entrances and numbered seats allowed crowds to move in and out of the Colosseum with reasonable speed.

• The Colosseum also was designed with gigantic awnings, or *vela*, to shade the crowds as well as a system of trapdoors underneath the field that permitted all sorts of special effects. Using a system of human-powered hoists, wild animals and scenery could “pop up” unexpectedly during events, to the delight of the audience. In addition, the wooden floor of the field could be removed and the stadium flooded in order to stage mock naval battles.

• A day of spectacle at the Colosseum—know as the *munus iustum atque legitimum* (“a proper and legitimate gladiator show”)—was organized by an individual sponsor who was known as the editor. The emperor was sometimes the editor, but not always. If the emperor came, he sat in the imperial box at the center of the north side of the stadium, and his reaction was scrutinized by the audience.

• A proper spectacle began in the morning with a splendid parade, the *pompa*, which was led by the editor’s standard bearers and typically featured trumpeters, performers, priests, and nobles. At midday, the next games, *ludi meridiani*, consisted of the execution of prisoners and barbarians. Finally, in the afternoon came the gladiator fights.

• To make all of these events happen flawlessly, a large crew of stagehands had to work as a team in the basement—the *hypogeum*—beneath the stadium. There in the heat and stench from the wild animals, the stagehands had to, on cue, hoist animals or scenery and provide the special effects that made the crowd roar.
The Fall of the Roman Empire

- Most historians today attribute the fall of the Roman Empire to a combination of a cultural flaw and larger environmental events. The cultural flaw was that the Romans took a static view of the world; they saw themselves as the peak of human civilization and believed that their political institutions would last not just for 1,000 years, but forever. Hence, we shouldn’t be surprised that they built roads and monuments that have lasted for centuries.

- However, embedded in such a view is a degree of inflexibility. Their static worldview meant that the Romans were not ready when change did come along, first in the form of epidemics and famine and then in terms of climate change and invasion.

- First, beginning in the 4th century C.E., an epidemic in Egypt killed off the slaves who grew the wheat that fed the urban masses. This food shortage resulted in a great deal of political unrest. Next, there was a mini–ice age in which the climate in the Northern Hemisphere cooled. The Romans gradually noticed that their typical crops (grapes and olives) were not growing as well north of the Alps. But even more troublesome was that climate change set off a chain reaction of migrations and invasions.

- In search of better lands, nomadic pastoral groups on the steps of Central Asia began pushing west and east, causing other groups to move as well. This domino effect had the result that the Germanic tribes east of the Rhine invaded the Roman Empire in late 4th century and eventually defeated the last Roman emperor in the west in 476 C.E.

Suggested Reading

Dale, *Timekeeping*.
Reynolds, *Windmills and Watermills*.
Reynolds, *Stronger Than a Hundred Men*. 
Questions to Consider

1. Like the Romans, do governments in the United States undertake major engineering projects to create a sense of commonwealth? What examples come to mind?

2. How does the arch overcome the limitations of stone as a building material, and how did it allow the Romans to create huge structures?
This lecture will focus on two great inventions that helped move Europe out of the economic and intellectual doldrums of the Dark Ages (500–1000 C.E.) and set the stage for the early modern world: waterwheels, the first major energy source beyond human muscle and animals; and clocks, the devices that Europeans used to define time, life, and labor. As you will learn, both devices are great inventions. Their development required some sophisticated thinking and a genuine creative leap, and they both significantly changed how people lived and thought about the world.

Waterwheels as Prime Movers

- Compared to inventions like the internal combustion engine or nuclear energy in the 20th century, waterwheels may seem rather quaint and irrelevant. However, waterwheels are every bit as important as gasoline engines or nuclear reactors, because waterwheels are the first example of a prime mover in human history.

- One way of divvying up the world of technology is to argue that there are tools and prime movers. Tools are the means by which humans shape materials (think of a hammer or saw and how we use these to shape wood). In contrast, prime movers are the sources of power that we use to drive tools (think of how a saw can be not only powered by a human muscle, but it can also be run by a waterwheel, as in a sawmill, or a gasoline engine, as in a chainsaw).

- The obvious advantage of a prime mover—whether it is a waterwheel or a gas engine—is that prime movers can deliver much more power that can be used for a given task. The waterwheel was the first prime mover invented by humans, and its discovery meant that people for the first time had a concentrated source of power that could be used to do bigger and more sophisticated tasks.
We don’t know who invented the first waterwheel, but archaeological evidence indicates that they originated in hilly regions north and west of Mesopotamia sometime before 300 B.C.E. One of the basic tasks that humans have confronted since the agricultural revolution is the challenge of grinding grain to make flour, and for centuries, this was done by using a mortar and pestle or a saddle quern, which is a stone roller on a hard surface.

Given how labor intensive this process is, a first step was to develop a rotary quern, in which the grain is crushed between the two stones—with the top one rotating and the bottom one stationary. A next step was that peasants sought ways to harness first animals, such as donkeys, to turn the millstone. Finally, some bright individual had the idea that the millstone could be connected to a wheel placed in a fast-moving stream. If the wheel had paddles, then the current would cause the wheel to turn, and one could connect the waterwheel to a millstone and have that turn as well.

This early form of a waterwheel is known as a Greek or Norse mill. Because the flow of water hits the wheel from the side, these wheels are sometimes known as horizontal waterwheels.

Clearly useful for grinding enough flour to feed several families or a small village, horizontal waterwheels spread across Greece and much of Europe. We know they reached Ireland and China by the 3rd and 4th centuries C.E. Many were still used by peasants in isolated mountain communities as late as the 19th century.

Because there was no gearing, Greek mills revolved slowly and could only process a limited amount of grain. While these horizontal waterwheels weren’t all that powerful, they did inspire Roman engineers to develop improved versions sometime in the 1st century B.C.E.

Borrowing the idea of gearing that had been developed by Hellenistic inventors for a variety of ingenious machines used for special effects in Greek temples, Roman engineers transformed the
Greek mill into a much more powerful prime mover. In particular, they used gearing so that the millstone could stay horizontal but the waterwheel could be turned 90 degrees and placed in a vertical position.

- In a vertical position, it became possible to power the wheel in three different ways: The water could flow underneath the wheel (undershot), the water could flow over the wheel (overshot), and the water could hit the wheel in the middle (breast wheel).

- As we now know, waterwheels can be used to power a whole range of technological enterprises—not only flour mills, but also saw mills, pumps for mines, bellows for iron foundries, and the spinning machines and power looms found in textile factories. But the Romans were not able to exploit this new prime mover fully. However, they did experiment with large-scale waterpower.

- Even as the Roman Empire disintegrated in the 4th and 5th centuries, the invading barbarians appreciated the potential of waterwheels, and by the time of Charlemagne, water mills were so plentiful that they were considered a good source of tax revenue.

- As the European economy recovered after 1000 C.E., water mills began to proliferate. During this recovery, Europeans discovered how waterwheels could be employed for a variety of industrial activities.

- Europeans learned that by providing a concentrated source of power, waterwheels allowed them to work large quantities of materials and, thus, the idea that power and machinery could replace human labor was introduced. In particular, the concentrated power of waterwheels encouraged entrepreneurs to undertake larger ventures. By producing more goods that could be bought and sold, waterwheels helped European society begin to grow after 1000 C.E.
The Evolution of Clocks

- In order to make sense of their lives and the natural environment around them, humans have traditionally sought out patterns. In terms of the passage of time, the most useful patterns are those related to the movement of the Sun and stars in the sky.

- One way to use the Sun to measure time is to observe how a shadow rotates around a stick as the Sun moves from sunrise to noon to sunset. The earliest type of timekeeper dating from as far back as 3500 B.C.E. was the shadow clock or gnomon, a vertical stick that casts a shadow.

- Taking advantage of their knowledge of geometry, the ancient Greeks developed many new forms of the sundial. Along with sundials, the Greeks also perfected water clocks or clepsydras, which utilize a simple principle that water flows or drips steadily out of a small hole in the bottom of a vessel.

- One can measure the passage of time by observing how the water level moves down relative to marks on the inside wall of the vessel. Alternatively, one can let the water drip out of one vessel and into another, in which one places a float and pointer that moves up as the water level increases. The pointer shows the passage of time as it moves up relative to a vertical indicator.

- Several prominent Hellenistic and Roman inventors—such as Archimedes, Heron of Alexandria, and Ctesibius—worked on improving clepsydras by adding gears and a dial indicator, gongs and trumpets to sound out the hours, or opened doors to show figurines.

- While monks in the Middle Ages relied on sand-filled hourglasses and clepsydras, it’s also likely that monks contributed to developing a new time-keeping device: the mechanical clock, which is powered by a falling weight. The trick is that you have to control the fall of a weight, letting it drop a little bit at a time. To control the descent of the weight, you need to invent a new mechanism: an escapement.
Although we don’t know for sure about who might have made this creative leap, we do know that between 1280 and 1320, there was an increase in the number of references to clocks and clocklike devices in church records, suggesting that a new type of mechanism had been devised.

The new mechanism was a verge-and-foliot escapement. In this mechanism, the weight is connected to a horizontal shaft that turns as the weight falls. The verge-and-foliot escapement is a really impressive invention in that it plays one force (the swinging arms of the foliot) off another (the descending weight). Even though they could lose 15 to 30 minutes per day and had to be regularly reset by consulting a sundial, verge-and-foliot clocks were all the rage from the 1300s to the 1500s.

The next improvement came thanks to the great scientist Galileo Galilei, who noticed in 1581 that a pendulum is isochronous—namely, that the period of the swing for small swing angles is constant and dependent only on its length. Near the end of his life,
Galileo designed a pendulum clock, but he died before he could build one. The pendulum took the place of the verge-and-foliot and controlled the fall of the weights.

- Picking up on Galileo’s idea, the Dutch astronomer Christiaan Huygens showed in 1657 how a pendulum could be used to regulate a clock, and he assigned this invention to Samuel Coster of the Hague, who built a version the following year.

- Huygens’s design was still not entirely accurate, and 10 years later, the English physicist Robert Hooke invented the anchor escapement, which permitted the use in clocks of a pendulum with a small swing. With the anchor escapement, the mechanical clock had achieved a high degree of accuracy, allowing it to be used for navigational purposes as well as countless other applications.

- As clocks started turning up in the towers of churches and town halls, people began regulating their lives by the chiming of the bells. Equally, the wealthy were fascinated by how such an ingenious machine could measure the passage of time, and they soon started asking for clocks not only for their homes, but to carry around with them.

- To create a portable clock—a watch—one needed to come up with an alternative to falling weights, and that alternative was the flat-coiled spring. One of the problems with using a coiled spring is that unlike a falling weight, which exerts some “pull” as it descends, a spring delivers more force when it’s fully wound up than when it’s nearly unwound.

- To compensate for this variation, Leonardo da Vinci sketched a device known as a fusee, which is a conical pulley attached to the drive shaft. As the spring unwinds, it engages a larger portion of the cone. The larger radius at the cone compensates for the weaker force of the spring, keeping the drive torque constant. Using a flat spring combined with a fusee, clockmakers produced the first
portable clocks around 1500, with some of the best being produced by watchmakers in Nuremberg, Germany.

Suggested Reading

Dale, *Timekeeping*.
Reynolds, *Windmills and Watermills*.
Reynolds, *Stronger Than a Hundred Men*.

Questions to Consider

1. Even though the Romans were great engineers, how do historians explain why they failed to have an industrial revolution?

2. At the heart of the mechanical clock is the escapement. In the earliest clocks, what did the escapement keep from “escaping”? 

3. How did clocks and the ability to measure time affect the rhythm of life and ways of thinking at the end of the medieval era? Why did clocks come to have such a central role in the modern era?
While some civilizations have used technology primarily for establishing social order or enhancing wealth, others have placed their priorities on using it as a tool to express spiritual meaning. This lecture investigates two examples of societies—Buddhist culture in East Asia and Catholicism in Europe—that developed inventive technology in the course of shaping and articulating religious ideas and beliefs. Specifically, you will learn about the inventions of the Buddhist pagoda and the Gothic cathedral.

The Pagoda

- Pagodas evolved from the burial mound in which remains or artifacts of the Buddha were interred. Gradually, the mound became a dome and then a bell-shaped *stupa*. In some cases, such as Borobudur on the island of Java, scores of *stupa* were incorporated as ornamental features studding the surface of a bas-relief–clad mound. In other places, the *stupa* grew to tremendous size and became the form of an entire building, as in the Shwezigon pagoda in Myanmar.

- After Buddhism crossed the Himalayas into China, the shape of the pagoda—the central element of the temple complex—became increasingly taller than the other buildings in the complex. Although brick pagodas date from the 6th century, it would appear that wooden pagodas were common, if not predominant, in China until about the beginning of the 10th century C.E., when a general shift from wood to brick took place.

- The design of pagodas evolved in a very different direction after the introduction of Buddhism into Japan during the 6th century. Like many early pagodas in China, Japanese pagodas were made of wood, but the social, climatic, and environmental circumstances of the archipelago exercised an influence that caused the material’s
use to become very different than on the mainland. In fact, the modifications to pagoda design in Japan probably caused wood to remain the material of choice long after it had lost favor in much of China.

- In China and Korea, pagodas had served the utilitarian function of lookout towers as well as the spiritual function of inspiration, and the upper levels were accessible via stairs or ladders. However, over time in Japan, stairs and ladders disappeared, and the upper levels of the buildings could only be reached with difficulty.

- Japanese climate forced further changes, particularly in terms of the size of the eaves. The islands are subjected to snow in the north, monsoons in the south, and the effects of wind and rain associated with any number of typhoons each year. Cumulatively, Japan has twice the average rainfall of China, a reality that pagoda builders needed to factor into their design.

- To protect foundations and wooden structural members from excessive rain and runoff, designers extended the eaves on each level to minimize the amount of water that would run down vertical supports and seep into foundations. They also covered the roofs of each level with tiles, ensuring that rain really would run off the building rather than cascade through its structural members.

Compared to those found in China, Japanese pagodas have a distinctive look.
• Compared to Chinese pagodas, on which the eaves tend to extend a maximum of 20 percent of their overall width, the eaves on Japanese pagodas extend to approximately 70 percent of the building’s width. This alteration in style gave the Japanese buildings a distinctive look that some people have compared to a pine tree with its boughs weighted down by snow.

• Just as the functional evolution of the building had its roots in social circumstance, and the visual design evolved from climatic pragmatism, the structure of pagodas descends from still another environmental factor: earthquakes.

• Located within the so-called Pacific Ring of Fire, the islands have been shaken with hundreds of serious earthquakes over the centuries. Amazingly, only two pagodas have collapsed from earthquakes over the last 1,500 years. The reason for this is the unusual structure of these buildings.

• As early as 607, with the construction of the Horyuji pagoda in Nara (the oldest multistoried wooden structure in the world), a means was in place of mitigating the motion introduced by tremors.

• The system that accomplishes this has several components. First, each level (or floor) of the pagoda is made up of interlocking vertical and horizontal (not diagonal) structural members. It also lacks load-bearing or stiffening walls, although it does include sheathing for the roof of the eaves and topmost floor.

• Some of the connecting joints are even designed to allow a limited amount of movement in response to sudden stresses (for example, zipper joints allow some horizontal movement). The overall effect of this arrangement of structural elements, joints, horizontal sheathing, and decorative elements is a stable but relatively flexible building.

• Next, the floors of the pagoda are simply stacked one upon another, held in place only by their own weight. Finally, when fitted
together, these modules create a hollow core, and it is in this space that the pagoda builders display their true brilliance. Suspended from the top of the shaft and extending nearly its entire height is the shinbashira, a square-sectioned “pillar” of cypress as much as two feet thick.

- When an earthquake occurs, all of the elements of the pagoda act in unison to dampen the motion transferred from the ground to the building. The ability of the craftsmen to fashion successfully a pagoda that can withstand such violent environmental forces was a function of trial and error—invention and discovery.

The Cathedral

- For a millennia and a half, including the height of Romanesque and Gothic building projects, the Catholic church exemplified Christian practice. One of the oldest and most impressive still-extant examples of a Romanesque (or Norman) cathedral is the Durham Cathedral in northern England.

- Begun in 1093, less than 50 years after the Norman conquest, its massive presence—with a nave 400 feet long and three stories high—must have made an impression about the future the country’s new Norman rulers had in mind. Because the initial stage of construction was overseen by William of St. Calais, recently returned from France, one can assume that the building exhibits a pan-Norman aesthetic.

- Durham marks the move away from barrel vaulting of the nave, favored in medieval churches, and is the first example of the ribbed-groin vaulting that would become widespread. Although the height of the nave allows a certain amount of light from above through the arcaded clerestory, the overwhelming feeling is one of great weight and somber darkness, exemplified by the gigantic pillars that separate the nave and side aisles.

- Even so, this was not enough to control the outward-thrusting load of the nave’s huge roof. To support the weight of the nave, the roofs
above Durham’s aisles conceal an innovation that will be exploited and developed almost beyond recognition by future cathedral builders: arched buttresses. Here, they are a utilitarian technology, hidden from view, but surprisingly soon, they will be brought out in the open and embraced.

- Across much of Europe, the middle of the 12th century saw improvements in agricultural and other technologies, which led to increases in trade, the growth of towns, and wealth. Civic pride and political gamesmanship as well as faith stimulated a competitive energy that focused on the construction of cathedrals as an expression that would convey a message on all three levels—spiritually, economically, and politically.

- This was very much the objective of Abbot Suger in his efforts to make the Abbey St. Denis (a destination of religious pilgrims and the resting place of Carolingian kings) the focal point of France’s “religious as well as patriotic emotions.” It is here, in a single-story ambulatory encompassing the apse and chapels (1140–1144) at St. Denis that the world first sees a clearly identifiable Gothic style typified by pointed arches and its other derivative elements: The proportions are more nuanced, the windows are larger, the columns are thinner, and the vaults are lighter.

- Although the Gothic style spread across Europe, lending its name to the period in the process, it is difficult to find a more compelling example of this elaboration of its structural elements than the one nearby at Notre-Dame de Paris.

- Construction of the church was the central element in a more extensive urban renewal project on the Île de la Cité in the center of Paris that included an open square, broad access roads, and the bishop’s palace. All of this began in 1163, barely 20 years after the completion of the apse at St. Denis, but the evolution of the structural style had already advanced a great deal.
Churches being built in England at this time continued to rely on linear horizontal impact, but in Paris, the vertical scale of the project grew to monumental proportions, a feature that is only amplified by the relatively compact dimensions of Notre-Dame’s floor plan.

The vertical orientation and increased height meant greater loads that would require a structural solution that was still true to the theological imperative. Furthermore, while dealing with the full height of the nave, the builders of Notre-Dame also wanted to enlarge the windows even more. The ultimate answer to these challenges was the flying buttress.

No one knows exactly where the first use of flying buttresses occurred, but they were in place at Notre-Dame sometime between 1190 and 1225. And they were already more than modest structural members. They grew from substantial stone piers abutting the outer walls of the aisle and apse, extending upward until they rose above the height of the roof of the cathedral’s lower flanks, ending in extended spires mirroring that on the crossing tower.

The buttresses reach out to the sides of the upper walls of the nave and choir, decreasing in thickness as they near their target, arched on the bottom, running diagonally on. They demonstrate a kind of orderly structural exhibitionism that expresses Suger’s thinking about proportion all the more fluently—and consequentially reinforces their status as not just technology in isolation, but as an essential articulation of spiritual meaning.

Structurally, the flying buttress allowed the creation of a system of internal and external skeletal elements. At Notre-Dame and elsewhere, this achieved the goal of reducing the area of solid, load-bearing stone walls so that they could be replaced with more and larger windows. Stained-glass windows were not new, but now the size of cathedral windows with tracery inserts presented an unprecedented opportunity.
A late-Gothic refinement of Suger’s ideas of proportion as an expression of God’s natural world is the development of the fan vault in England during the late 15\textsuperscript{th} and early 16\textsuperscript{th} century. From below, the radiating ribs of the vault resemble the form of a fan, but in actuality, the ribs form a segment of a concave cone, curving outward from the base in one dimension as they radiate in another.

### Suggested Reading


Icher, *Building the Great Cathedrals.*

“Shake, Rattle, and Roll,” *The Economist.*

### Questions to Consider

1. How do the design of pagodas and cathedrals reveal fundamental theological differences between Buddhism and Catholicism?

2. How does the *shinbashira* in Japanese pagodas help protect these shrines from earthquakes?

3. How did the flying buttress permit cathedral builders to erect taller buildings? Why was this theologically important?
The next two lectures will examine several inventions that moved along the Silk Road from China to Europe. This lecture focuses on paper and printing, both of which were invented in China and then moved East through the Islamic world to Europe at the end of the Middle Ages. By comparing East and West, you will learn that while people use great inventions to shape their destiny, there’s nothing automatic or deterministic about how technology shapes history. Instead, you will learn how people use inventions in response to the needs and imperatives of their environment and society.

East Meets West

- As the saying goes, “East is East, and West is West, but the twain shall never meet.” People often use this saying to claim that China and the Islamic world are separate from and different than Europe and America. Yet for the history of technology from 500 to 1500, nothing could be further from the truth. During these centuries, ideas and machines moved steadily East to West, from Chinese and Islamic societies to Europe.

- Much of this technology moved along the Silk Road, a trade route that crossed Asia to connect China and India to the Mediterranean world. This route took form in the 1st century B.C.E., when rulers in Central Asia developed a strong cavalry that could fight off nomadic tribes who raided trade caravans.

- Over the next 1,000 years, these caravans brought Chinese silk, Persian carpets, and steel swords from Damascus in Syria to Europe. In return, the Chinese took back gems, jade, gold, and silver. Goods changed hands along the route, with Arab, Persian, and Indian merchants acting as middlemen.
Not only a trade route, the Silk Road was also a highway for technology. The Chinese invented paper, printing, gunpowder, and the magnetic compass—all of which came to Europe via the Silk Road. Craftsmen journeyed along the Silk Road and introduced new designs for waterwheels, windmills, and other machines.

And new ideas moved East to West as well. For instance, Arab merchants adopted an Indian numerical system using 0 through 9 because it permitted the rapid calculation of costs and prices. European traders on the Silk Road also began using these numerals, and when they arrived in Europe at the end of the 12th century, they were called Arabic numerals.

The Evolution of Paper

In order for printing to evolve, it was necessary to develop a new material on which to print: paper. To make paper, you take a fibrous material—such as linen, wood, cotton, or straw—and you beat it to a pulp. To further soften the fibers, you might boil them with wood ash (alkali). You then wash the pulp and spread it onto porous screens to dry.

Since ancient times, important documents and books in Europe were written on parchment, which is the untanned skin of sheep or goats. As you might expect, parchment was expensive; to make the equivalent of a book with 200 pages, you would need the skins from a dozen sheep. Hence, the real cost in producing a book in medieval Europe was not having someone write the text by hand but, rather, the cost of the materials.

In China, the scholars and bureaucrats who served the emperor were faced with a similar problem. Although they didn’t use parchment, they too were confronted by the high cost of using bamboo tablets and silk for their books.

Sometime in the 1st century B.C.E., the Chinese began making paper that they used in a variety of ways—for clothing, small domestic objects, and wrapping objects. According to tradition, a
scholar in the emperor’s court in 105 C.E. began advocating that books be written on paper instead of bamboo tablets and silk.

**Printing in China**

- Once paper was available, the Chinese began investigating ways to reproduce numerous copies of materials for two reasons. The first was the spread of the Buddhist religion in China. In order for people to learn about this new religion, the Buddhists believed it was important to make copies of prayers and sacred texts available to the people, and this prompted them to investigate printing. As an initial step, Chinese Buddhists around 200 C.E. printed texts and pictures by carving letters and images onto wooden blocks, which were covered with ink and pressed against sheets of paper.

- A second factor prompting the Chinese to develop printing arose from the examination process by which government officials were selected. These examinations were based on the mastery of a series of books related to the teachings of Confucius. Because the examinations were open to all who had the time (and money) to read and study, the government felt obliged to make copies of these texts widely available.

- In addition, the Chinese imperial government also printed and distributed books to keep its bureaucrats informed about new agricultural, engineering, and military techniques. The Chinese government saw printing as a means of disseminating key ideas and stimulating a common culture.

- For the Chinese, block printing worked reasonably well. The blocks for a particular book were often held for generations by a single family of printers, who ran off copies whenever there was sufficient demand. In some cases, hundreds of thousands of copies of a particular work were printed. Private printers produced not only religious texts but also volumes of poetry, alchemy, and biography as well as playing cards.
The Chinese continued to experiment with a variety of printing techniques, such as color printing and movable type. In about 1045 C.E., an experienced block printer, Pi Sheng, began experimenting with making individual Chinese characters in clay and then assembling them on a tray to form the text.

Subsequent printers in China further perfected the technique by developing metal type. However, because the Chinese language requires up to 40,000 separate characters, movable type did not seem practical to Chinese printers, and it was not pursued vigorously.

**Printing in Europe**

Because block printing was more successful in China than movable type, it appears that the idea of block printing was somehow transmitted from East to West in the 13th century. The idea may have traveled with the Mongols, who learned about it when they conquered China in 1276 and who surged into Russia and eastern Europe about the same time.

Equally, examples of block printing, such as playing cards, were carried back by Venetian merchants, and these examples may have prompted craftsmen to experiment with printing. At about the same time, Europeans learned about paper from the Muslims, who were manufacturing it in Spain. Hence, by the end of the 1300s, block-printed items (playing cards, religious pictures, and a few books) were being produced in northern Italy and southern Germany.

Because the Roman alphabet employs a small number of standard letters, printers throughout Europe were tempted to experiment with movable type. While it appears that several printers in France and Holland used movable type in the 15th century, credit is traditionally given to Johann Gutenberg of Mainz, Germany.

By 1447, Gutenberg was operating a print shop in Mainz, and this shop is credited with producing 50 different titles. The most famous was the Gutenberg Bible, which far surpassed in beauty and
workmanship all the books produced up to this time. By printing a masterpiece, Gutenberg contributed decisively to the acceptance of the printed book as a substitute for the handwritten book.

**How Did Printing Change the World?**

- The development of printing played into two trends in European culture. On the one hand, printing was stimulated by the economic prosperity of Italian cities and the Renaissance; as the merchant and middle classes grew more prosperous and literate, they demanded more reading material. In response, Italian printers produced secular works, such as the newly revived Greek and Roman classics, the stories of Italian writers, and the scientific works of scholars.

- On the other hand, the rise of Martin Luther, the ensuing Protestant Reformation, and the subsequent religious wars between Catholics and Protestants were heavily dependent on the printing press. Just as the Buddhists in China had felt it was important to make sacred texts available, so early Protestants fervently believed that Christians should be able to read the Bible and decide God’s message for themselves.

- As a result, printers in northern Europe turned out vast numbers of religious books, such as Bibles, Psalters, and missals. Because these texts were to be read not only by the clergy but by ordinary people, these books were printed in both Latin and the newly emerging vernacular languages (i.e., Italian, French, German). In addition, groups on both sides of religious and political controversies in the 16th and 17th centuries published pamphlets in an attempt to persuade people to join their cause.

- Between 1450 and 1500, no less than 40,000 separate works were printed in Europe. This was more titles than had been produced in Europe prior to 1450. During this period, the number of printers increased rapidly as well. In Italy, for instance, the first press was established in Venice in 1469, and by 1500, the city had 417 printers.
• The first printing press was brought to England in 1476 by William Caxton. Printing also followed the Europeans to the New World. In 1539, Juan Pablos set up a press in Mexico City, and Stephen Day established a press in Cambridge, Massachusetts in 1638.

• Printing thus illustrates how a new invention can follow different trajectories in different societies and have different impacts. In China, printing was developed as a means for integrating Buddhist and Confucian ideas into the general culture. Printing helped the Chinese government to promote a common culture through the texts used for the exams to become a bureaucrat.

• In contrast, printing in Europe was drawn into the unfolding intellectual, religious, and political changes. Rather than creating a common and continuous culture, it stimulated debate and division.

• It was used by Renaissance scholars to introduce new secular and scientific ideas. Protestants relied on printing to produce new Bibles that could be read and interpreted in ways that challenged the traditional teachings of the church.

• Different political groups used pamphlets to put forward new ideas. And because people preferred to read in their native tongues and not in Latin, printing contributed to the development of multiple languages in Europe. Rather than helping to create a single culture
(as in China), printing permitted Europeans to develop diverse (and even conflicting) national cultures.

**Suggested Reading**


Liu, *The Silk Road in World History.*


**Questions to Consider**

1. How did new religions—Buddhism in China, Protestantism in Europe— influence the way printing developed?

2. Should Gutenberg be celebrated as the “inventor” of printing in the West?

3. How did the development of printing contribute to the Renaissance and the scientific revolution?
Another great invention from China—gunpowder (which led to the invention of guns)—developed differently in China and Europe, illustrating how different military situations and social structure affect the course of technological change. In this lecture, you will explore the invention of gunpowder and cannons and how these technologies dramatically altered history on both sides of the world. This lecture will take a comparative approach, examining how these inventions took different trajectories in the East and the West.

**The Invention of Gunpowder**

- Gunpowder is a mixture of saltpeter, sulfur, and charcoal. These three substances are finely crushed and mixed together so that particles of each are touching one another. When gunpowder is set on fire, the sulfur burns first because it has a low ignition temperature of 261°C.

- The sulfur ignites the charcoal, which is a hot, clean fuel. The temperature of the burning mix quickly reaches 335°C, which is the ignition point for saltpeter, which is a nitrate salt—typically potassium nitrate.

- When saltpeter ignites, the nitrate radical releases extra oxygen, which dramatically speeds up combustion of the sulfur and charcoal. Combustion now produces hot gases, which go in every direction, causing a bullet to travel at high speed down a gun barrel or a bomb to fly apart.

- Gunpowder was first formulated in the 9th century by Chinese alchemists who were looking for the elixir of life, hoping that they could come up with something that would allow them to live forever. They had identified saltpeter and sulfur as interesting...
ingredients and seem to have tried a variety of combinations in their search for the elixir.

- Within a century or so, gunpowder was taken up by the army in the Song dynasty and was used initially as an accelerant in fire lances, handheld flamethrowers that consisted of a bamboo tube that could shoot flames at short range for five minutes or so.

- Soldiers soon realized that the right mix of saltpeter, sulfur, and charcoal could be used not just to ignite the fire lance, but also had the explosive power needed to propel bits of metal or potsherds that would injure the enemy. This resulted in what we would today call a mortar.

- Over time, the Chinese replaced the bamboo tube in the fire lance with a tube made of bronze or iron. Around 1100, the Chinese military made a further discovery that you could capture all of the force of the explosion of the gunpowder by replacing the bits of metal with a projectile like a ball. By making a close fit between the projectile and the wall of the tube, the force of the explosion of the gunpowder caused the projectile to exit the tube with great force and a high velocity.

- If you made the tube longer, it became possible to give the projectile a specific trajectory and aim it at a target. Through these steps, the Chinese invented the first guns and cannons. The oldest surviving gun dates from 1288.

- Note that gun and cannon barrels need to be carefully formed, usually by drilling out the barrel. Gun barrels made by rolling a sheet of metal into a tube couldn’t contain the gunpowder blast and generally blew up in the soldier’s face. Hence, guns and cannons were expensive weapons from the start.

- Troops in the Song dynasty also used gunpowder to power rocket bombs that were used to repel the armies of foot soldiers invading
from Mongolia, Tibet, Thailand, and Vietnam. The Chinese employed gunpowder in landmines as well as incendiary bombs.

- Because they were dealing with large hordes of attackers, rockets proved to be very effective weapons; they were lightweight, cheap, and could be launched against the horde so as to create both injury and confusion.

**Gunpowder Comes to Europe**
- Gunpowder came to Europe via the Silk Road or through the Mongol invasions in the early 13th century. After they overthrew the Song emperors, the Mongols regarded the Chinese as worthless and turned to Arabs and Europeans to be minor officials and help rule their state. Hence, the Mongols readily shared ideas with Arabs and Europeans.

- Because the challenges were to either break down the walls of fortifications or sink naval ships, Europeans used gunpowder in cannons. Europeans seem to have had an advantage in that they could develop stronger iron for use in cannons than the Chinese.

- Because gunpowder and cannons were expensive, only kings could afford them, and they used them to defeat rebellious townspeople and powerful dukes; as a result, gunpowder contributed to the emergence of strong monarchies by the start of the early modern era.

- In addition, Europeans further refined handguns and muskets that could be carried by individual soldiers. The earliest handguns—known as *hakenbüchse* (literally, “guns with a hook”), rendered in English as “harquebuses”—were made in Germany in the 14th century. They needed two men to operate them and were so heavy that they were fired from a stand.

- By the mid-1400s, *hakenbüchse* had evolved into matchlocks, muskets or shoulder guns with a smoldering fuse and trigger that could be aimed and fired by one man. To create matchlocks, a small hook was attached to a lever. On the hook was placed a smoldering wick, and when the soldier pulled on the other end of the lever—the
trigger—the wick swung down and ignited the gunpowder through a touchhole in the barrel.

- Because guns were reordering the political and military world of the Renaissance, many of the leading thinkers and artists devoted themselves to improving weapons in order to secure or maintain the support of powerful patrons.

- Among the great minds that studied weapons was Leonardo da Vinci, and around early 1500, he sketched an alternative to the matchlock. Instead of dealing with the smoldering wick, Leonardo devised a wheel lock. Much like a modern cigarette lighter, the device consisted of a steel wheel that, when rotated, struck a flint, giving off sparks that went through the touchhole.

- German gunmakers enthusiastically adopted the wheel lock and used it initially to make hunting guns for the nobility because it was too delicate and expensive to place in the hands of ordinary soldiers.

- Eventually, in the 18th century, the wheel lock on shoulder guns was replaced by the flintlock, in which the trigger controlled a hammer-like lever mounted with flint that struck a steel piece mounted next to the touchhole.

- Wheel locks, though, gave rise to the first pistols, favored by cavalrymen because they could ride and shoot them at the same time. Wheel lock pistols also became the preferred weapon of highway robbers, leading to laws in many places in the 16th century limiting who could own pistols.
• Note that there is a difference between using the words “gun” and “rifle.” A rifle is a specific kind of shoulder weapon with a barrel in which spiral grooves are machined on the inside wall. The groove imparts a spin to the projectile as it travels down the barrel, with the result that the projectile travels outside the gun on a straighter trajectory. Consequently, rifles were much more accurate than smoothbore muskets.

• You have to be very careful with a front-end loading rifle, lest you spoil the grooves as you load your charge and rifle ball and ram it home. Because it took longer to load rifles than muskets, European armies didn’t take up rifles until well into the 19th century.

• Further, it was not really until American gunsmiths began turning out thousands of hunting rifles for pioneers—first by hand and then by machine—that it became feasible to produce enough rifles for an army.

• It required highly skilled metalworkers to make guns. It was difficult to make barrels that would not explode, and great craftsmanship was needed to assemble the precision trigger mechanism. As a result, gun making was restricted to a handful of cities possessing a large number of skilled artisans. Venice was one such city, and its armaments factory at Brescia became famous for the matchlock muskets it provided to the armies of Europe.

• Gunpowder, cannons, and handguns changed the face of warfare in Europe. These new weapons were extremely effective, but they were also extremely expensive. It was much more costly to equip an army of musketeers than one of archers. The use of cannons inflicted enormous damage on buildings and made it necessary to build elaborate fortifications to protect castles and towns.

• For all of these reasons, it was now beyond the means of powerful individuals to support private armies. By the 16th century, war had become the reserve of kings and other rulers who were able to raise taxes to pay for soldiers and armament.
From East to West

- Gunpowder and guns are truly Chinese inventions that appeared in China centuries before they were used in Europe. Because the Chinese were dealing with large invading land armies, they put much effort into developing rockets to attack the hordes.

- In contrast, Europeans took a greater interest in cannons, which could be used to break down fortifications and, thus, defeat troublesome counts holed up in castles or unruly townspeople hiding behind town walls.

- Again, we see how different circumstances prompted people to take the same invention—gunpowder—and use it to create very different weapons. There is no single best way to develop a new technology; it depends on the circumstances.

- Like printing in the East and West, gunpowder and rockets were effectively deployed by the Chinese to maintain a degree of homogeneity in their culture—to keep out invaders—while gunpowder in Europe fed into the forces that were separating people into different nation-states.

Suggested Reading

Kelly, *Gunpowder*.

Needham, *Science and Civilisation in China*.

Questions to Consider

1. Why did the Chinese prefer to use gunpowder to develop rockets while the Europeans used it to develop cannon and guns?

2. How did gunpowder and cannon shift the balance of power in Europe away from nobles and toward kings?
Telescopes and Microscopes
Lecture 11

The scientific revolution of the 15th and 16th centuries was dependent on the invention of optical instruments. These instruments allowed natural philosophers to make observations that prompted the creation of new fields that today we call astronomy, biology, physics, and chemistry. In addition, instruments like the telescope and the microscope helped establish the scientific method. In this lecture, you will learn that the telescope and the microscope are great inventions because they allowed people to revolutionize the way they saw and understood the natural world. These inventions are at the heart of our modern notion of what science is.

Light and Refraction

- Telescopes and microscopes work according to the same principle. When you look at an object, the light reflecting from it strikes your eye at a high angle. However, when you look at the object from a distance, lights radiating from those same points on the object now strike your eye at a much lower angle.

- If you artificially manipulate the angle at which the light strikes your eye, increasing the angle so that it approximates what it was when you stood closer to the object, then the object will appear much larger. Telescopes and microscopes do exactly this by using lenses to change the angle of the light before it hits your eye so that things seem bigger when you look through the lenses.

- Although modern instruments have many more components, early instruments follow these basic principles using just two lenses: the larger primary lens, or objective nearest the target; and the secondary lens, or eyepiece at the opposite end of the instrument.

- As light reflects from any given point on a target object, it radiates off in many directions. First, a telescope or microscope clarifies the
image of the target by collecting some of that dispersed light and redirecting it through the objective.

- The size and curvature of the objective can be manipulated to refocus the light at a particular distance from the lens; this is the focal length of the objective lens. Having refocused the light from the target, the eyepiece can then be placed in such a way as to bend the light again so that it strikes the eye at an “artificially” high angle, thereby making the target appear much larger.

- The same magnifying effect can be achieved using concave (curving inward) or convex (curving outward) lenses. Most early instruments used a pair of convex lenses, or more rarely—and most famously in Galileo’s telescope—a combination of a convex objective and a concave eyepiece.

- The phenomenon of refraction—light changing direction—as it entered a pool of water had been observed in nature for millennia before anyone was able to adequately explain the phenomenon.

**The Telescope**

- Identifying the “true” inventor of the telescope is problematic if not impossible. What seems certain is that various combinations of convex and concave lenses were tried in England, the Netherlands, Italy, and Germany during the late 16th and early 17th centuries.

- Traditionally, credit has gone to a Dutch spectacle maker named Zacharias Janssen in 1604, but he even said he based his instrument on an Italian account from around 1590, which historians have speculated to be Giambattista della Porta’s *Magiae Naturalis*.

- Hoping to keep control of his idea while trying to get credit for it by publishing a description, della Porta supplied an intentionally vague description of how he used a combination of convex and concave lenses to magnify distant objects.
• There is hard evidence that in 1608, the Dutchman Hans Lippershey demonstrated a telescope to Prince Maurice of Nassau. There exists an account that chronicles their ascent of a tower in The Hague from which they were able to see the clock tower in Delft and cathedral windows in Leiden.

• The secret to Lippershey’s success was the addition of a diaphragm with a 10-mm aperture in front of the objective. This eliminated much of the distortion introduced at the edges of the lens.

• Lippershey requested a patent for his invention, but others (including Janssen) claimed that they could produce instruments with similar abilities. Regardless of their origin, the idea of a telescope spread quickly across Europe—from the first half of the 17th century onward.

Ancient telescopes were able to help people watch Venus pass in front of the Sun.
Many historians credit Galileo Galilei (1564–1642) as the “effective scientific inventor of both the telescope and the compound microscope,” but Galileo modestly declined the honor, referring particularly to the telescope as a Dutch invention. He was, however, the first person to conduct detailed experiments on the relative size of the aperture and its placement with regard to the objective.

While it did not initially occur to Galileo to train his telescope on the Moon, it very soon attracted his attention. What Galileo saw when he looked at the Moon served to undermine much of what people had assumed about their universe—and ultimately how they understood their place in it.

According to the tenets of Aristotelian thought embraced by European philosophers and theologians, the heavens were a separate reality from Earth. While the terrestrial world was imperfect and malleable, the heavens were believed to be perfect, immutable, and constant. The Sun and Moon were unchanging objects orbiting man’s Earth as it occupied the central position beneath a canopy of stars. Man and Earth were alone, unique in the universe.

With his telescope, Galileo discovered that the universe was a much larger, much more complex place. Previously a cautious Copernican, Galileo accumulated more and more evidence indicating the implausibility of a geocentric universe.

It had become clear to him that the heavens were no longer simply the backdrop for a solitary, central Earth surrounded by a canopy of stars, and as the whole nature of the physical universe changed, the conception of human existence within it began to change as well.

It would be up to Johannes Kepler not only to confirm and mathematize Galileo’s finding about the planets, but also to devise a standard lens configuration for telescopes using two convex lenses.

Indeed, over the next century, major scientific figures devoted as much energy to inventing better optical instruments as they did to
formulating scientific theories. Both Christian Huygens and René Descartes spent a great deal of time on calculating how to grind precise lenses, and they struggled to come up with a machine that could perform the grinding precisely.

- The great Isaac Newton decided to sidestep some of these problems by inventing an entirely new kind of telescope, a reflecting telescope that magnified objects by using a curved mirror instead of lenses.

The Microscope

- Although Galileo is credited with reengineering a microscope from his original telescope, the development of microscopes was advanced rapidly by both lens makers and natural philosophers in the middle of the 17th century.

- During this formative period, individuals experimented with two kinds of microscopes: some that were based on telescopes and used multiple lenses and others that employed only a single lens.

- The major difference between microscopes and telescopes is the orientation of the eyepiece; in microscopes, the rounded surface of the convex eye lens faces the target, but it is reversed to face the viewer in telescopes.

- Microscopes with multiple lenses were developed and promoted by Robert Hooke, the first secretary of the newly formed Royal Society, which was one of the first scientific societies in the world.

- Born in 1635 on the Isle of Wight, Hooke studied natural philosophy at a university and thereafter became Robert Boyle’s assistant. Tempted away by the Society in 1663, he embarked on a new course of research under its auspices.

- In 1665, Hooke published his seminal work, *Micrographia*, which included both his observations on a wide variety of specimens and a description of the instrument he used. Two of Hooke’s most famous observations in *Micrographia* detail a flea—the original drawing of
which was 16 inches in length—and a thin layer of cork. It was in the description of this second specimen that Hooke coined the word “cell” to describe the structure he observed.

- In contrast, Antony van Leeuwenhoek pioneered a single-lens microscope. Leeuwenhoek was born in Delft in the Netherlands in 1632, but he did not emerge as a microscope maker and microscopist until 1673. In that year, his name first appears in the archives of the Royal Society, where Hooke was already well established.

- Leeuwenhoek was notoriously secretive about both his instruments and his methods of observation. He never let anyone outside of his immediate circle look through one of his microscopes. Nonetheless, his results were amazing and were detailed in more than 200 letters, many of them illustrated, that he sent to the Royal Society.

- Leeuwenhoek’s instruments were very different from Hooke’s—and much more effective. First, they were small, handheld devices: a brass plate with an aperture into which a single spherical lens was mounted. A specimen was mounted on a pin and manipulated by a series of screws. The entire thing fit in the palm of the hand, and Leeuwenhoek was reputed to have polished lenses made from fragments of glass.

- Remarkably, the best of his instruments magnified more than 250 times, allowing him to study bacteria and spermatozoa. Even in the 19th century, one of Leeuwenhoek’s lenses was judged to be superior to some of the best the era could produce. Biologists of that time and later still found it necessary to consult Leeuwenhoek’s records to determine if they were simply duplicating his work.

**Suggested Reading**

Ford, *Single Lens*.

Wallach, *The Long Route to the Invention of the Telescope*
Questions to Consider

1. Why was it so significant that Galileo used his telescope to observe how several moons were orbiting Jupiter?

2. How did the telescope and microscope change how early scientists formulated and proved theories?

3. If new instruments were at the heart of the scientific revolution in the 17th century, do they continue to play a similar role in science in the 21st century?
This lecture focuses on Prince Henry of Portugal (1394–1460), who became known as Henry the Navigator, along with a careful examination of ships, navigation techniques, and winds. In this lecture, you will learn that Henry was an important—indeed, pivotal—figure in history. Henry marks the beginning of the modern world because he was the first to create and use technology to deliberately shape the destiny of his nation. And this notion that people can use technology to change their destiny is a hallmark of the modern world.

European Expansion (1350–1600)

- A key idea that Europeans in the Middle Ages (circa 500–1300 C.E.) shared with their Roman predecessors was that society was relatively static; the rhythms of daily life, the patterns of settlement, and the social hierarchy of peasants, lords, and kings all seemed to be timeless and fixed.

- However, beginning in the 1300s, an improvement in the climate (it got slightly warmer in Europe) and the influx of new ideas and products from the Arab world prompted Europeans to begin to think that change was possible for individuals (such as merchants), cities (such as Italian city-states), and kingdoms. And change seemed to be predicated on the acquisition of more wealth.

- Some wealth was being acquired slowly and steadily by more effective techniques in farming and trades, but the fastest way to acquire wealth was to tap into the riches of India and China. But blocking the way for merchants and princes who wanted the wealth of the East was Venice.

- Since the 9th century, Venice had controlled trade with the East (via the Byzantine and Arab empires) and had grown rich and powerful. Venetian ships, or galleys, sailed regularly across the eastern
Mediterranean carrying cargoes of spices, gold, and silk; other Italian port cities (such as Genoa) did their best to compete with the Venetians.

- Various European monarchs and merchants looked with envy at the Venetian monopoly and wished they could get a “piece of the action.” But only one individual took a technological approach to the problem: Prince Henry of Portugal (1394–1460), who was the third son of King John I of Portugal and Philippa of Lancaster. His brother would become Henry IV of England.

- Because the Muslims didn’t want the Portuguese to participate in the trade and because the Portuguese couldn’t defeat the Venetian navy in the Mediterranean, Henry decided that the best way was to figure out how to sail along the African coast and around into the Indian Ocean. By doing so, he would outflank both the Venetians and the Muslims.

- Based on his wide reading of travelers’ accounts, Henry was convinced that there either had to be an oceanic passage below Africa or at the very least people in lower Africa with whom the Portuguese could set up trading relations. Determined to get access to the riches of the East, Henry sent 15 expeditions between 1424 and 1434 to sail down the coast of Africa.

- The modern mind, accustomed to motorized ships that can go anywhere they want, may think that all Henry had to do was order sailors to follow the coast of Africa until they came to the Indian Ocean. Hence, when captains and crews refused to do so, a modern person would conclude that they were irrational and must have been afraid of giant sea monsters.

- In reality, the captains and crews were really quite sensible. The problem is that sailing ships need favorable winds and currents to get to and from different ports, and the prevailing winds and currents along the African coast eventually are in the wrong direction for a ship trying to sail down the coast.
• When crews got to Cape Bojador (a few hundred miles south of Lisbon), the currents and wind are such that sailing ships can’t go any further. For sailors, Bojador was, for all intents and purposes, the end of the world. You couldn’t go any farther, and it had nothing to do with sea monsters.

• To overcome this problem, Henry brought together the people needed to gradually develop a system that integrated three innovations: better ships, systematic information about prevailing winds and currents, and new navigation techniques.

• In terms of talent, Henry was fortunate in that he was able to draw not only on ambitious and experienced mariners from various parts of Europe, but also mathematicians, mapmakers, and astronomers from the Islamic world.

• It’s important to note that Henry and his experts didn’t come up with this system all at once and then go out exploring. As with many important technological breakthroughs, Henry spent decades (1420s to 1460s) bringing all of the pieces together, and the work was then continued by King John II after Henry died.

Celestial Navigation

• If a Portuguese caravel wanted to sail from Lisbon to somewhere on the African coast, the captain could begin by using his compass to set a southwest course and be carried by the northeast trade winds at the top of the South Atlantic gyre.
However, at some point, the captain would have gone far enough south, and it would be time to turn east and use a westerly wind to reach the desired point on the African coast. So, how could the captain know he had gone far enough south and should turn east, back toward Africa?

In our terms, the captain needed to sail as far south as the latitude of the desired African port and then turn his ship east and sail across the latitude. But how could he know his latitude? The answer is celestial navigation.

As it turns out, the captain of this hypothetical Portuguese caravel could take advantage of a basic astronomical principle: Along any line of latitude, the angle between the horizon and the North Star in the sky is always the same. We call this angle the declination; the Portuguese called it the altura.

So, if the captain knew the altura of the African port and measured the same angle while still at sea, he would then know he was on the same latitude as the port and should turn eastward.

Therefore, to navigate by the stars, you need three things: an instrument for measuring the altura of stars (quadrant), information showing the altura with particular destinations and later latitudes (astronomical tables), and a means to keep track of direction and position (plotting board).

Because it was not necessarily all that easy to learn how to measure the altura and then use the tables and plotting board to determine a ship’s position, Henry set up a school for navigators and developed rules and procedures (systematic applied knowledge).

Moreover, he found it best to send a personal deputy from his court to make sure that the navigator did his job and that the captain and crew followed orders. Often a junior knight, this deputy also collected information in Africa about the local population, goods available for trade, and geography.
- The early voyages of the 1420s not only provided information about wind and currents, but also allowed Henry to claim the Azores and Madeira for the Portuguese king. Henry’s ships regularly called on another set of islands off of Africa, the Canaries, but these had already been claimed by the Spanish.

- The king gave Henry complete control over the trade with all of these islands, and Henry sent colonists to the Azores and Madeira. In Madeira, Henry promoted the production of sugarcane and wine, both of which proved to be lucrative crops.

- Through the 1440s and 1450s, Henry’s caravels reached farther and farther south on the African coast, reaching as far as the Senegal River. There, Henry’s emissaries were able to trade for gold, and they were able to secure enough that the Royal Mint in Lisbon began issuing gold coins known as cruzados.

- Henry’s emissaries also unfortunately kidnapped blacks, who became slaves. Henry seems to have sanctioned the slave trade in the belief that black slaves brought to Europe could be baptized and, hence, have their souls saved.

- Henry supervised and financed voyages himself until his death in 1460. By then, he had demonstrated that his system of ships and navigation was reliable and that trade with Africa could be lucrative.

- Henry’s vision was continued by his nephew, King Afonso V, and grandnephew, John II. Under their guidance, Portuguese navigators explored the rest of the African coast and reached India.
  - In 1488, Bartolomeu Dias reached the Cape of Good Hope at the southern tip of Africa.
  - In 1498, Vasco da Gama reached India.
  - In 1500, Pedro Cabral discovered Brazil.
  - In 1516, the Portuguese reached Macao in China.
The Riches of the East

- Throughout the 16th and 17th centuries, the Portuguese set up forts and trading posts in Africa, Brazil, India, and China. Aware of Portuguese success, the Spanish pursued a different strategy: If the Portuguese were sailing and controlling the South Atlantic, then they would sail west to the Indies, and hence, they supported first Christopher Columbus to the Caribbean and then Ferdinand Magellan across the Pacific.

- However, because it was too far across the Pacific, the Spanish decided to concentrate on colonizing the New World (where they found plenty of gold, silver, and slaves).

- The English, like the Spanish, sailed west, looking for the Northwest Passage around the top of North America, but established both trading posts and colonies in the New World.

- The Dutch and French imitated the Portuguese and pursued trading posts in Africa, Asia, and the Americas.

- Thanks to Henry and his successors, Portugal’s success was technological. They designed better artifacts (ships), developed new practices (navigation) and acquired new information (star charts), and understood and utilized forces of nature (wind and currents).

- To be sure, other groups had developed these individual innovations. Northern Europeans had improved ship hulls, the Chinese had invented the compass, and Muslims provided the lateen sail and astronomical knowledge. But what the Portuguese did during the 1400s was weave these elements into a highly effective system.

- Henry’s contribution was to start and manage this process of integration and to inspire people to design new ships and take them to new places. In so doing, Henry established a key idea for the West: Individuals and nations can bring about economic and political change by deliberately improving technology.
Law, “Technology and Heterogeneous Engineering.”
Russell, *Prince Henry “the Navigator.”*

**Questions to Consider**

1. How were the ships developed by the Portuguese suited for sailing on long voyages in the Atlantic?

2. How did Prince Henry’s crews take advantage of the wind, ocean currents, and stars in order to sail further south, toward the bottom of Africa? Is this an interesting case of using technology to work with nature as opposed to conquering nature?

3. Is Henry a harbinger of the modern world or, rather, a stereotypical character of Renaissance Europe?
One of the ways of thinking about the role of inventions in human history is to visualize history as alternating between long eras where the technology changes slowly punctuated by moments of dramatic change. These dramatic moments of change—even though they may take decades to play out—are often referred to as revolutions. In this lecture, you will learn that the industrial revolution was not driven by just one invention but, rather, was the result of several technological breakthroughs that happened at the end of the 18th and the start of the 19th centuries.

The Industrial Revolution

- Most historians assume that there have been three revolutions, as follows.
  - Agricultural revolution (circa 10,000–8000 B.C.E.)
  - Industrial revolution (1750–1925)
  - Information revolution (since 1950)

- Most historians today like to talk about two industrial revolutions, which involved different countries, different technologies, and different consequences.
  - First industrial revolution (1750–1850)
    - Involved coal, steam, iron, machine tools, and factories.
    - Was driven by craft or hands-on knowledge.
    - Started in England and spread to Europe and America.
  - Second industrial revolution (1875–1925)
    - Involved oil, electricity, steel, mass production, and big business.
• Was driven by a mix of practical knowledge and science.

• Started in America and spread to England, Europe, and Japan.

• Like the agricultural revolution, the industrial revolution was a set of technical and social activities that produced rising income per capita (more wealth for everyone, even with population rising) and rising income by gains in productivity (more output).

• The inventors, engineers, and entrepreneurs of the first industrial revolution got more output by devising new technologies that provided economies of scale (activities, machines, and buildings could be bigger), economies of speed (processes could be done faster), economies of coordination (more output resulted by carefully planning how the work was done—often discussed as the division of labor), and economies of location (choose to locate your factory where you can get cheaper inputs, but this often means that some inputs have to come to you—transportation).

• Before you can improve productivity, there has to be an increase in demand for goods; otherwise, why should inventors invent new machines or entrepreneurs organize new businesses?

• In Europe, population and economic patterns changed dramatically between 1400 and 1700. Improvements in food production resulted from new land being brought under cultivation and the existence of windmills and waterwheels for processing grain. Regions began to specialize in wine, cheese, and olive oil—whatever they could do best. There were also new crops, such as the potato and maize corn.

• European exploration and trade also contributed to economic growth. There was new wealth (gold and silver) from the New World. There were new luxury goods from America and Asia—including tobacco, chocolate, coffee, tea, silk, and porcelain—that merchants and landed nobility wanted to consume. In addition, urban merchants grew rich and constituted new political force.
In response to growing population and wealth, many activities expanded from small-scale household enterprises to “industrial” operations, including brewing beer, glassmaking, and soapmaking.

Many of these operations involved heat, and economies of scale could be achieved by building bigger fires to increase temperature and pressures. To get hotter fires, people used more wood or charcoal. Charcoal burns hotter because are impurities driven off, leaving nearly pure carbon.

**Coal and England’s 17th-Century Environmental Crisis**

- By the time of Queen Elizabeth I, England’s forests were disappearing so fast that the Crown placed restrictions on which forests could be cut down. In response, early industrialists began using coal instead of wood or charcoal.

- Coal was created over millions of years as temperatures and pressures underground converted rotting plant matter from the Carboniferous Period (about 300 million years ago) into nearly pure carbon.

- Pound for pound, coal delivers far more heat (BTUs) than the equivalent amount of wood or charcoal, but you can’t simply substitute coal for wood or charcoal.

- In glassmaking, coal introduces impurities that spoil the glass, so reverberatory furnaces, in which fire is separated from glass, were developed. In brewing, coal was used to dry the malt but left an awful taste. In the 1640s, brewers experimented with baking coal in ovens to drive off impurities, which resulted in coke, the residue of coal. It was made by heating bituminous (soft) coal in a beehive oven; the heating drives off impurities and leaves nearly pure carbon.

- Thanks to significant coal deposits around Newcastle in the north and Wales, England enjoyed a significant energy advantage as compared to France and the Netherlands, its major industrial competitors.
Throughout the 17th and 18th centuries, English coal mines expanded, sometimes using wagonways with rails to move the coal efficiently out of the mines. These wagonways were the starting point of railroads.

Demand for coal in cities such as London, Birmingham, and Manchester prompted entrepreneurs to build an extensive system of canals. High thermal energy output and low cost made coal the ideal fuel for steam engines, which were developed in the 1700s.

A New Age of Iron

The iron that is most useful to us is actually an alloy of the elements iron and carbon. By varying the trace amounts of carbon, you can make iron that is suited to different purposes.

- 0.10% to 0.25% wrought iron
- 0.25% to 2.1% carbon steel
- > 2.1% cast iron

Generally speaking, wrought iron and steel are more ductile than cast iron, which is brittle.

Iron was well known in the ancient world and was used by the Chinese, Greeks, and Romans. However, because of the high melting point of iron (1,300°C), they were unable to melt iron and, hence, manipulate it in as many ways as they could other metals. Consequently, all iron tools and weapons in ancient and medieval times were made of wrought iron.

In the smelting process, the impurities would burn off or melt away, leaving a spongy mass (known as a “bloom”), which the blacksmith would work by hammering, heating, and cooling (annealing).

During the late Middle Ages, Europeans learned how to melt iron in a blast furnace using charcoal to create pig iron, which could then be cast into a variety of products, such as pots and cannons.
• Cast iron, however, is brittle and cannot be used to make products such as hardware, nails, locks, and tools. To make these products, the pig iron still had to be worked by a blacksmith wielding a forge and anvil; by heating and pounding the iron, the blacksmith was able to make wrought iron, which was both stronger and more malleable (able to bend or flex without breaking).

• In 18th-century Britain, the growth of markets at home and abroad prompted entrepreneurs to investigate new ways to produce more and better cast iron. One of these entrepreneurs was Abraham Darby I (1676–1717), a Quaker ironmaster at Coalbrookdale on the River Severn, outside the city of Birmingham.

• Having worked as a malter (someone who dried the hops used in brewing beer) and then as a copper smelter, Darby was familiar with using coke as a furnace fuel in place of charcoal. Coke was desirable because it burned hotter and longer than charcoal.

• Before Darby, no one had been able to figure out how to use this better fuel to make cast iron—in part because most coke contained too much sulfur, which spoiled the iron.

• Taking advantage of low-sulphur coke available near Coalbrookdale, Darby was the first to successfully smelt iron using coke, and doing so permitted him to produce high-quality cast iron in quantity.

• Rather than produce just pig-iron bars, Darby perfected techniques for casting all sorts of products in the sand floor of his foundry.

Pig iron could be cast on the foundry floor—not only into bars but a variety of products, such as pots and cannons.
He became famous for cast-iron pots, which sold well all over England and Wales.

- Another product cast at Coalbrookdale were cylinders for Newcomen steam engines. These cylinders were a demanding product. Not only were they quite large—often 2 to 3 feet in diameter and 8 to 10 feet tall—but they also had to be machined precisely.

- In order for a steam engine to work—that is, to not let the steam escape or air come into the engine’s cylinder—the piston and cylinder had to be machined with tolerances on the order of one-hundredth of an inch.

- Following in his father’s footsteps, Abraham Darby II (1711–1763), mastered the art of making such large castings, and in 1763, Coalbrookdale delivered a 7-ton cylinder with a diameter of 74 inches and a length of 10.5 feet.

- The Darbys also promoted the use of cast iron in new applications. To demonstrate the strength of their product, Abraham Darby III (1750–1791) designed and built a 100-foot cast-iron bridge over the Severn at Coalbrookdale. The bridge is made up of 70-foot arches that were cast as single pieces and then bolted together. This impressive bridge conveyed to the world the strength of cast iron, and engineers began using it for beams and columns in buildings and to make gears and other machine parts.

- Just as the Darby family concentrated on improving cast iron, other entrepreneurs experimented with ways to increase the production of wrought iron from pig iron. Ultimately, this problem was solved by Henry Cort (1740–1800), who brought together several ideas to develop the techniques of puddling and rolling. Like the Darbys, Cort used coke as a fuel, but he borrowed from glassmaking the reverberatory furnace. Unlike a blast furnace, in which the iron and fuel are mixed together, a reverberatory furnace keeps the
pig iron separate from the fuel and thus prevents the fuel from contaminating the iron.

- Although some engineers were initially suspicious of wrought iron produced using Cort’s process, his techniques could be scaled up so as to produce large quantities of wrought iron cheaply. After the 1780s, large puddling furnaces became widespread, and they replaced the small, independent forges that had previously provided most of Britain’s wrought iron.

- Thanks to coke and new techniques pioneered by the Darbys, Cort, and others, the output of the English iron industry grew dramatically. Between 1788 and 1796, the output of the industry doubled, and it doubled again in the next eight years. As output soared, the price of iron dropped, and manufacturers began using iron to make a wide range of goods. By the early 19th century, iron became the material of choice for making steam engines, machines, ships, rails, buildings, hardware, stoves, pots, and tools.

Suggested Reading

Ferguson, “Metallurgical and Machine Tool Developments.”

Freese, Coal.

Trinder, The Darbys of Coalbrookdale.

Questions to Consider

1. How did coal and iron create economies of scale that were exploited in different industries?

2. Why did Abraham Darby I switch from using coal to coke to make iron?

3. Why did Abraham Darby III build the Ironbridge at Coalbrookdale? What was he trying to demonstrate?
The inventions of the industrial revolution were all about increasing output. As you will learn in this lecture, the steam engine contributed to this revolution in productivity in two ways: economies of speed (machines of all sorts could be run faster than if they were powered by humans or animals) and economies of coordination (when combined with the division of labor, it was possible for factory owners to making more goods more cheaply). This is well illustrated by the example of pin making, but the story of pin making also offers other important lessons about technology and the distribution of economic power in society.

The Steam Engine

- While the steam engine is often attributed to James Watt (1736–1819), Watt’s engine was actually only an improvement of an earlier engine invented by Thomas Newcomen (1663–1729).

- While selling iron hardware, Newcomen came into contact with mine owners in Devon and Cornwall, England, and soon learned that the biggest challenge confronting them was pumping water out of the mines. In Cornwall, the tin mines already extended for thousands of feet under the sea, and the only way the mines could continue to operate was if the water could be removed quickly and continuously from the shafts and tunnels.

- As mines got deeper in the 16th and 17th centuries, engineers developed a number of ways to pump water out of the mines. On the surface, each of these techniques was powered by horses using a gin, and hence, one of the significant costs of operating a mine was feeding and maintaining the team of horses needed to pump water continuously out of the mines.

- In 1698, Thomas Savery (1650–1715) patented a steam pump for lifting water out of the mines. In Savery’s pump, high-pressure
steam was first admitted into an iron cylinder; cold water was then poured on the outside of the cylinder, condensing the steam inside and creating a vacuum. The vacuum, in turn, sucked water up a pipe and thus provided a pumping action.

- To pump the water, the valves were adjusted, and high-pressure steam was then introduced into the vessel, which in turn pushed the water up the delivery pipe and out of the mine. Savery’s pump was not automatic and required a boy to manipulate the valves to let the steam or cold water in at the right moments.

- To pump water a significant height, the Savery pump also required significant steam pressure; for instance, to raise water 180 feet required a steam pressure of 80 pounds per square inch. Such pressures were well beyond the capability of existing boilers and cylinders. Despite its impracticality, a syndicate of

When steam engines were first introduced, the power of the new engines was measured in terms of horsepower because mine owners wanted to know how many horses the new engines would replace.
London investors purchased the patent for Savery’s pump and set themselves up in 1716 as “The Proprietors of the Invention for Raising Water by Fire.”

- At the same time that Savery patented his impractical steam pump, Newcomen was developing his own engine. Drawing on the practical knowledge he had gained from business, Newcomen built a test model consisting of a piston moving up and down inside a vertical cylinder. The piston was connected to one end of a pivoted beam while on the other end of the beam was a pumping mechanism. As the piston moved up and down, it caused the pivoted beam to rock up and down, which in turn operated the pump.

- Newcomen immediately realized how his engine took advantage of both steam and atmospheric pressure, and he quickly devised an automatic mechanism that let steam and a squirt of cold water into his cylinder at the right moments.

- Because his engine required a coal-fired boiler, Newcomen installed his first successful large-scale engine at a coal mine in Tipton in 1712. Newcomen secured this contract via friends in the Baptist church.

- Even though his engine bore little resemblance to Savery’s pump, Newcomen was dismayed to learn that the London syndicate viewed his invention as being covered by their patent. As a result, Newcomen was forced to work with the syndicate, who erected Newcomen engines but never bothered to tell anyone that the engines were invented by Newcomen.

- Nevertheless, Newcomen’s engine soon came into general use for mine pumping throughout Britain in the 1720s, and they were erected at mines in Austria, Hungary, Belgium, France, Germany, and Sweden. In 1753, the first Newcomen engine was erected in America at a mine in New Jersey.

- Despite the success of his engine, Newcomen gained little in the way of riches or fame during his lifetime; when he passed away in
1729, one newspaper briefly mentioned the death of “Mr. Thomas Newcomen, sole inventor of that surprising machine for raising water by fire.”

- Newcomen’s engine was improved upon by James Watt in the 1770s. While repairing a demonstration model of a Newcomen engine at the University of Glasgow, Watt discovered that the efficiency of atmospheric engines could be increased by squirting cold water into a separate condenser connected to the main cylinder.

- As long as one caused the steam to condense somewhere in the system, the pressure inside the cylinder would be less than the atmosphere, thus causing the piston to move. Using a separate condenser meant that Watt’s engine avoided the problem of continually heating and cooling the entire cylinder, and thus, his engine used less coal to fire the boiler.

- In addition, Watt connected his rocking beam to a flywheel, which meant that his engine could not only pump water but could also provide rotary power for different machines.

- Watt was careful to patent all of his improvements, and he was lucky to secure a savvy businessman, Matthew Boulton, as his partner. Between 1775 and 1800, the partnership of Boulton and Watt held a monopoly on steam engines in England, installing nearly 500 engines across the country.

- Unlike the Newcomen engine, which was best suited for pumping water out of mines, Watt’s improvements, such as the planetary gear and the speed governor, meant that his engines could be used to power all sorts of machinery that required rotary power.

- Watt’s engines could turn faster than the humans, animals, and waterwheels that they replaced, meaning that the machines ran faster and produced more output in the same amount of time. Hence, the steam engine, invented by Newcomen and perfected by Watt,
contributed to the industrial revolution by providing economies of speed.

Pin Making

- The real impact of the steam engine came when it was coupled with an organizational innovation, the division of labor. Together, these two innovations caused a dramatic jump in manufacturing output and profoundly changed what daily work was like.

- By the 1770s, many people in Britain sensed that something was profoundly changing daily life. While Boulton and Watt were sure that it was their steam engine, others, such as the economist Adam Smith (1723–1790), thought that the big change was social and not technical. Smith was convinced that soaring output was a result of the reorganization of work in factories.

- Since ancient times, craftsmen had produced goods of all kinds by undertaking all of the steps involved to create a particular good in their own household or shop. As the economy grew in the 16th and 17th centuries, however, entrepreneurs began experimenting with separating out these different activities and hiring workers who possessed a particular aptitude for one task or another.

- This separation of production into different tasks is known as the division of labor. Since the entrepreneur spread the work out among workers who lived in different cottages, this system was known as “putting out” and is the basis for why we call small enterprises “ cottage” industries.

- By the 18th century, entrepreneurs realized that you didn’t need to send the work out to different cottages and, in fact, that you gained significant advantages by having individual workers perform specific tasks in a single factory. By having everyone working under one roof, the factory owner could not only monitor quality, but he could also coordinate all of the tasks to boost the quantity.
To call attention to this revolution in work, Smith used the example of pin making in his famous book, *The Wealth of Nations* (1776). There, he argued that while a typical worker could not make a single pin on his own in a day, the division of labor made it possible for a worker to produce 4,800 pins per day.

Notably, for Smith, the marvel of this division of labor was not only the huge gain in output, but also the possibilities it held for social mobility. Smith believed that poor people might go to work in such a factory, see how the division of labor was performed, and then go off and start their own new enterprises.

Smith thought that the division of labor would revolutionize society by eliminating classes—that the working class would eventually meld into a single middle class who shared the same values of buying and selling their time or goods or services.

In using pin making as an example of what was happening in British industry, Smith was certainly on to something about the changing face of work. But Smith’s example of pin making, according to economist Michael Perelman, was something of a fairy tale: a charming story that conveyed an important idea or feeling, but one that could never be true for everyone.

Smith was right that the division of labor was altering the workplace, but Boulton was also right that the changes were also coming from new machines and new sources of power.

It was the integration of social and technical innovations—the division of labor with new machines and power sources—that caused the dramatic gains in output. You can’t have one without the other.

**Suggested Reading**

Perelman, *The Invisible Handcuffs of Capitalism*.

Questions to Consider

1. If Thomas Newcomen invented the steam engine before James Watt, why does Watt’s name turn up more frequently in history books?

2. How important was Matthew Boulton to Watt’s success?

3. Why did Adam Smith not mention machinery in his discussion of pinmaking? Do we continue to share Smith’s belief that new inventions (like the personal computer) will empower ordinary people? How realistic is this?
Because steam engines needed fuel, because the new machines needed lots of raw materials as input, and because factories had lots of goods to ship to customers, the industrial revolution involved significant improvements in transportation. In Britain, the expansion of markets at home and globally prompted businessmen and government officials to seek to improve transportation in the mid-18th century, and these improvements gave Britain an advantage as industrialization took off. In terms of transportation, this lecture specifically focuses on canals and railroads.

Canals

- Because many of the basic inputs to factories—coal or cotton or minerals—were bulky, industrialists first sought to improve water transportation. It was (and still is) cheaper to ship bulky materials by water than using roads or railroads.

- A canal isn’t just a ditch, but a system of civil engineering works that need to be carefully laid out and coordinated. Canals need to be level so that there is always sufficient water for the boats and so that the water doesn’t flow downstream and out of the canal. While slight irregularities in the lay of the land can be dealt with through cuttings and embankments, canal engineers had to often include other elements to a canal.

- To get across valleys, it sometimes made sense to put the canal in a bridge or aqueduct that spanned the valley. At other times, they dug tunnels through hills rather than go around them. But the most ingenious device engineers developed was the pound lock, which consists of a chamber within which the water level can be raised or lowered, connecting either two pieces of the canal at a different level or the canal with a river or the sea.
Generally speaking, there are three kinds of canals: lateral canals, which follow an existing stream or river and take advantage of the existing level riverbed; contour canals, which minimize the need for cuts and locks by following the natural contours of the landscape; and summit canals, which connect two river systems by going over the mountain range that separates the rivers.

Canals have their origins in ancient China, where lateral canals were established as far back as the Warring States period (481–221 B.C.E.). Although the Chinese appear to have invented the first pound lock, many of their canals ran through relatively level terrain, so they didn’t use very many of them.

As the economy in Europe gradually recovered between the 12th and 15th centuries, merchants sought to expand trade and business in their towns and cities by improving transportation in their region.

Hence, merchants in the Netherlands, northern Germany, and northern Italy built canals to complement the navigable rivers in their regions. In doing so, canal builders often puzzled over the
problem of how to get their boats from a river or harbor to a canal that, due to the lay of the land, might rise slightly above the river.

- Further, canal builders often added dams and gates (known as flash locks) across rivers, which ensured a more reliable level of water along all the stretches of the river. However, because other entrepreneurs were erecting water-powered mills along the rivers and the opening and closing of the flash locks wreaked havoc with the flow of water on which the millers relied, canal builders soon found themselves in court arguing with the mill owners.

- To overcome both of these problems, canal engineers created the pound lock. The earliest lock in Europe seems to have been used by 1373 in Vreeswijk in the Netherlands.

- Other engineers soon realized that pound locks could be used not only to solve problems with mill owners or where canals met harbors, but could also be used to build summit canals over the mountain ranges separating two river systems.

- Locks up to this time had relied on vertical gates, known as portcullis gates because they moved up and down like the gates on castles. Because they were vertical, they limited the height of the boats moving on canals, and in response, Leonardo da Vinci designed the mitre gate, which consists of two doors that swing horizontally out of the basin and into the canal. All subsequent canal locks used (and continue to use) Leonardo’s design.

- British entrepreneurs began building their own canals in the mid-18th century. The opening of the Sankey Canal in 1757—followed by the Bridgewater Canal in 1761, which halved the price of coal in Liverpool and Manchester—led to a period of “canal mania” in Britain. Over 100 canals were built between 1760 and 1820.

- In Britain, canals were paid for and promoted by wealthy landowners and industrialists. The self-taught engineer James Brindley (1716–1772) was commissioned to build one of the first
canals in order to carry coal from the duke’s coal mine at Worsley, Lancashire, to Manchester in 1761.

- Over the next century, engineers built over 4,000 miles (6,500 km) of canals, connecting London in the south to York in the north. To pay for the canals, canal operators charged individuals a toll for bringing their own boats onto the canal. While a few canal boats had sails, others were pulled by horses that walked along the canal path. Steamboats were generally avoided because the wake of paddlewheels caused too much turbulence in the limited water in the canals.

- In England, canals contributed to rapid industrialization in two ways: They significantly reduced the cost of shipping bulk goods, such as coal and other inputs that factory owners needed; and they permitted manufacturers to ship their products all over England, thus enlarging the domestic market for manufactured goods.

- America had its own version of “canal mania,” which lasted from the 1790s to the 1830s. During this period, several eastern port cities launched canal projects to funnel grain, timber, and other products from the Midwest to them.

- While it is easy to assume that canals just “disappeared” with the coming of the railroad, in reality, canals continued to be the best way to ship bulk goods through the 19th and into the 20th century. The canal system in Britain is still maintained for pleasure boating, and the Erie Canal—now the New York State Barge Canal—continues to carry freight.

**Railroads**

- As Watt improved his steam engine in the 1760s and 1770s, several inventors tried to make a steam vehicle. For a road vehicle, it was not possible to use a low-pressure atmospheric engine because of the size and weight of the engine cylinder. Instead, inventors had to develop a lighter and more compact engine that used high-pressure steam to push the piston.
• High-pressure engines, however, meant that engineers had to develop stronger boilers (to prevent explosions) as well as more precisely machined pistons and cylinders. The high-pressure steam engine was perfected in America by Oliver Evans (1755–1819) and in England by Richard Trevithick (1771–1833).

• In 1769, Nicolas Cugnot (1725–1804) in France built a road locomotive with a high-pressure engine. Cugnot hoped that the French army would use his vehicle to haul cannons, but the army rejected it because few roads were smooth enough on which the locomotive could operate.

• In 1800, Evans drove a steam vehicle along the streets of Philadelphia, and in 1801, Trevithick built a successful steamer that climbed Camborne Hill in Cornwall and achieved a speed of 8 miles (13 km) per hour.

• The lack of smooth roads limited the use of all these vehicles, so engineers experimented with placing the vehicles on rails. Rails had been used to provide a smooth surface to guide wheels as early as the 3rd century B.C.E. in China, and they were used in Europe for moving carts in and out of mines in the 16th century.

• In 1804, at the Penydarren ironworks in South Wales, Trevithick placed one of his high-pressure engines on wheels and used this locomotive to pull 5 cars with 70 men and 10 tons of ore along a track. To popularize his idea of a steam railroad, Trevithick erected a small circular track in London in 1808.

• By 1820, there were a number of small steam railways operating at mines and other industrial sites in Britain, and another engineer, George Stephenson, began manufacturing locomotives for use on these private lines. In 1821, a group of investors convinced Parliament to pass an act permitting them to set up a railway between the towns of Stockton and Darlington as a business and to charge for carrying passengers and freight.
• Although the investors initially planned to have horses haul freight and passengers, Stephenson convinced them that it would be more profitable to use a steam locomotive to pull a train of cars. In 1825, using his engine *Locomotion*, Stephenson operated the first public train in the world, carrying 12 wagonloads of freight and 22 passenger carriages. Stephenson followed up his success with the Stockton and Darlington Railway by helping establish a second longer line, the Liverpool and Manchester Railway, in 1830.

• These two railways were not only technical triumphs but also business successes. The technical and financial success of these two lines established the concept of a railway. Previously regarded as a form of short-haul transportation suited for use in mining, the railway was now seen as a new form of long-haul transport for both passengers and freight.

• Once their feasibility and profitability had been demonstrated, railways developed rapidly, and lines were constructed connecting major cities throughout Britain and continental Europe in the 1830s. In Britain, investors built the railways with minimal government intervention, but with the result that there were often competing railways on the most lucrative routes. In contrast, on the continent, railways were either built or closely controlled by the national governments, which helped ensure that lines served the social and economic needs of each country.

• One curious aspect of the development of railways in Europe was the use of different track gauges (the distance between the tracks) in different countries. Even today, these different track gauges mean that rail traffic between western Europe and Spain, Portugal, and the Russian republics has to be transferred at the frontiers unless it is carried on cars with changeable or variable-gauge axles.
Suggested Reading

Bernstein, *Wedding of the Waters*.


Wolmar, *The Great Railroad Revolution*.

Questions to Consider

1. How can canals and railroads be seen as “economic accelerators”? Along with new machines and steam engines, how are they necessary ingredients for industrialization?

2. Why did railroads replace canals?
Food Preservation
Lecture 16

Whereas individual families once grew, preserved, and cooked much of their own food, over the course of the 19th and 20th centuries, most of these activities moved from the home to the factory. As you will learn in this lecture, one impetus for this shift was that in the 19th century, as workers moved from the countryside to urban factories, it became necessary to develop new techniques for processing and preserving food. However, the effects of industrial food processing are far more extensive than making it possible to produce quantities of food in one area for consumption in another.

Canning
- To a great extent, the story of industrial food preservation is the story of hot and cold. Canning, a key early technique, was invented by Nicolas Appert, a chef and confectioner in Paris. In 1795, he began experimenting with ways to preserve foodstuffs, placing soups, vegetables, juices, dairy products, jellies, jams, and syrups in heavy glass bottles and sealing them with cork and wax. He then placed the bottles in boiling water to cook the contents.

- Although Appert didn’t know it at the time, putting the bottles in boiling water and raising the temperature killed the bacteria that caused food to turn bad—a principle subsequently proven by Louis Pasteur. Appert’s preservation method was soon imitated by other entrepreneurs, including Peter Durand.

- In order to secure a British patent in 1810, Durand began using metal cans instead of glass bottles. Durand sold his patent to Bryan Donkin and John Hall, who set up the first canning factory in 1813 to provide preserved food for the British army.

- By the 1820s, canned food could be readily purchased. Cans were initially made individually by hand, a process that limited
production to about 60 per tinsmith per day. This meant that the supply of cans was both limited and expensive until other inventors created machines for mass producing cans.

- In less than two generations, mechanized can manufacturing solved this problem by increasing worker productivity by more than 2,500 percent. Most “tin cans” were actually made of iron or steel with a tin coating because the iron imparts a taste to the food.

- In 1861, Isaac Solomon of Baltimore discovered that the boiling time required to make contents safe could be reduced from 6 hours to 30 minutes. He accomplished this by adding calcium chloride to the water, thereby raising its boiling temperature from 212°F to 240°F. With the water boiling at a higher temperature, the time in the bath was reduced.

- While canning had the obvious benefit (when done properly) of protecting the consumer, it also had economic advantages

The pork-packing process in a slaughterhouse in Cincinnati, Ohio, was referred to as a “disassembly line.”
for suppliers and processors. Canning encouraged agricultural specialization: Rather than produce for local consumption, farmers could concentrate on maximizing yield per acre of a single crop for processing, distribution, and sale without regard to the wants or needs of any individual market. Industrial monoculture only became viable through the advent of industrial food preservation.

“Shrinking” Food

- Another advantage for food processors was that food preservation generally and canning in particular also had the effect of “shrinking” food by eliminating nonconsumable or unnecessary food components. Two examples of this are condensed milk and corned beef.

- The American entrepreneur Gail Borden had something of an obsession for preserving food through dehydration. He realized that removing the water content of food not only increased its edible life, but it also reduced its size and weight, thereby making it more portable—a characteristic he thought pioneering Americans would appreciate and pay for.

- Unfortunately, in the 1840s, Borden’s initial efforts in developing the meat biscuit were met with a less-than-enthusiastic public embrace. Fortunately for Borden, he found a far better subject for dehydration and condensation: milk. His greatest challenge here was not simply preserving milk, but maintaining its physical quality and taste. He found that he could produce a satisfactory end product by using a vacuum pan for boiling and evaporating the milk, but he could not create an industrially useful process because the milk foamed and stuck to the surfaces of the pan.

- Seeking a simple, practical solution, Borden greased the pan, and the problem went away. In 1856, he received both American and British patents for his process.

- When the Civil War broke out, the Union Army requisitioned Borden’s output. Solomon’s technique for accelerating the
production process (discovered the same year) increased Borden’s industrial capacity dramatically. Even so, the 16 quarts per day produced by his New York plant fell far short of the military’s demand, a situation that eventually motivated him to license his process to other producers.

- Prior to the Civil War, the demand for canned goods was still limited, and canners maximized production and minimized risk by diversifying their product line. Processors near the coast, particularly in the area around the Chesapeake Bay, processed fruits and vegetables during the summer and fall and seafood during the winter and spring.

- However, after the war, with many servicemen having acquired a taste for canned foods, demand increased. Within a decade of the war’s beginning, canning grew from 5 million to 60 million units annually. This increase in market volume brought new products and specialization.

**Refrigeration and Fresh Meat**

- While some meat was canned, there was also a large market for fresh meat, prompting various inventors in the mid-19th century to experiment with ways to chill meat for shipping.

- While ice was commercially harvested in America for use in home iceboxes and refrigerated railroad cars and ships, the major breakthrough was mechanical refrigeration, which was patented by a Floridian named John Gorrie in 1851.

- Although his machine could make ice, the invention of the ammonia compressor by the German Carl von Linde in 1876 made the process easier and more reliable. Within a dozen years, there were 200 commercial ice plants in the United States.

- With this technology at hand, the challenge of “preserving” or extending a food’s period of freshness became appealing for entrepreneurs. Doing so would not only reduce waste by prolonging
“shelf life,” but it would also open up entirely new marketing opportunities for processed fresh foods.

- This was most true in the meatpacking industry. People had eaten preserved meat that had been salted, smoked, or dried for centuries, but cooling and mechanical refrigeration technology offered the potential to eat “fresh” meat long after it would have spoiled under natural conditions.

- Before the middle of the 19th century, fresh meat had to come to the city under its own power: alive and kicking. Local slaughterhouses would then process these animals (hogs and steers) for quick sale and consumption. This was an uncertain proposition, and consequentially, the availability and pricing of fresh meat prevented it from being a staple on most tables.

- Although there were many steps in the process by which meat got from the Western plains to the to the Eastern dinner table, the crucial link in the network was the refrigerated railcar. With refrigeration, animals channeled to a convenient central location (Kansas City or Chicago, for example) were slaughtered and then distributed for sale.

- The efficiencies of industrial slaughter notwithstanding, this model allowed processors to reduce feed costs, minimize loss of animals in transit, and avoid shipping costs on the 35 percent of the animal’s weight that went into the refuse heap.

- One of the most important characters in this story was Gustavus Franklin Swift. After successfully implementing refrigerated railcars, Swift next concentrated on streamlining the processing of the product before shipment.

- Swift built on the idea of the mass production of foodstuffs through the construction of an innovative corollary, precursor of the moving assembly line: the disassembly line. In fact, the disassembly line originated in Cincinnati hog butchering, where it was in place by the mid-1850s.
This division of labor not only led to tremendous improvements in efficiency, but it also led to specialized methods of dealing with parts of the animal that had previously been thought of as waste.

The development of new products by the meatpacking industry had other unanticipated effects. Because many of these products (such as canned meats) did not require refrigeration, packers found themselves with unutilized rail refrigeration capacity.

**Frozen Foods**

- While the benefits of cooling had become obvious, it was still thought that freezing was more destructive than preservative—the ruinous effects of a killing fall frost on a vulnerable crop too unequivocal to suggest otherwise. It would be up to Clarence Birdseye to prove that under the right circumstances, the very opposite was true.

- Ice fishing in Labrador during the winter of 1912, Birdseye casually tossed his catch on the ice beside him, where it quickly froze in the 20-degrees-below-zero cold. Later, Birdseye was shocked to see that the fish was resuscitated when he dropped it into a bucket of water.

- Although he did not know it at the time, because the size of ice crystals is proportional to the speed at which a liquid freezes—faster freezing means smaller crystals—the fish’s cells had been left undamaged by the small ice crystals produced by its very rapid freezing.

- Birdseye also discovered that fish frozen in this way tasted much better than slowly frozen fish, in which cell damage released fluids that produced unpleasant changes in its physical character and taste.

- As if that were not lucky enough, Birdseye just happened to be well placed to take full advantage of his discovery; he was a resident of Gloucester, Massachusetts, one of America’s largest commercial fishing ports. In fact, fish could be frozen before they reached port,
minimally processed on the on-deck cleaning table, or even tossed straight from the seine or trawl directly into the freezer.

- Nevertheless, there were difficulties to overcome. Experimentation revealed that not all foods behaved the same; varying cell structures required different temperatures or freezing times to best preserve quality.

- Existing refrigeration units depended on convection—the passage of cold air across the surface of an object to be cooled or frozen—and Birdseye found this process to be generally too slow as well as too difficult to control. The only answer was for Birdseye to develop his own equipment and techniques.

- Freezing by conduction proved to be fast, effective, and suitable for industrial processing. Food was prepackaged in thin containers and sandwiched between metal plates and then was cooled to as much as 25 degrees below zero. This way, the quality of various frozen foods could be optimized because the temperature of the plates—and, hence, the freezing time—could be precisely controlled.

Suggested Reading

Boorstin, *The Americans*.

Cronon, *Nature’s Metropolis*.

Steinberg, *Down to Earth*.

Questions to Consider

1. How is meatpacking another great example of the division of labor?

2. How important is refrigeration to the story of what foods we consume?
Sanitation has been a necessary constant concern of all humans. The distinctly temporal task of disposing human excrement was important enough to warrant mention in the Bible, which took the practical approach of digging a hole and burying it. A Hindu text suggested defecating no less than the length of an arrow’s flight from camp. While this suggestion worked well when humans lived in small, dispersed settlements, it became dangerous and unneighborly when people gathered in larger, more concentrated settlements. In this lecture, you will learn about the evolution of sanitation.

Toilets in History

- Many ancient civilizations understood the necessity of disposing human waste, but the Romans appear to have dealt with the problem on a larger scale and to a more thorough degree than others.

- Near the Roman amphitheater, a row of more than two dozen toilet openings stretches cheek to cheek above the length of a channel through which gray water flowed, where it carried theatergoers’ contributions away to disposal in more appropriate circumstances.

- Running in parallel in front of these seats is a second channel where freshwater flowed; when people had finished their business, a stick and sponge apparatus could be dipped into the water, and cleaning of the relevant parts could be performed.

- Given the complete lack of privacy and extreme proximity of the seats, there is no indication of public toilet inhibition or personal embarrassment—reactions that only seem to arise later with “advances” in toilet technology. The remains of similar technology are found among Roman ruins throughout the ancient world.
• In 13th-century Britain, things were dramatically different. In the era’s most sophisticated structures, castle toilets were comprised of an opening, high up in the wall, where a holed bench provided a drafty perch. From this height, excreta cascaded down the wall into a dry moat, leaving a smelly, unsanitary trail behind.

• Rather than being swept away by a stream of water, these accumulated leavings were carted off at night by the gongfermour (gong farmer) to be disposed of in dumps outside of town, subsequently to be used for fertilizer. Unsavory as this may have been, practices similar to these were employed in the maintenance of urban privies into the late 19th century.

• In Tudor England, some wealthy urbanites enjoyed the convenience and comfort of indoor toilets as well as the use of wads of woven flax or fluffy tufts of wool treated with madder or woad to clean and soothe their bums. Nevertheless, these toilets did not remove excreta from the home, merely dropping it into cesspits—often right next to the kitchen—which needed to be emptied and the contents carted away.

• Thanks to her godson, John Harington, Queen Elizabeth I not only enjoyed indoor plumbing, but also what may be the world’s first flush toilet. One of two remaining examples is on display at the Gladstone Pottery Museum.

• Nearly two centuries later, in 1775, Scottish watchmaker Alexander Cummings received a patent for a flush toilet with an all-important innovation: an S bend in the drainage pipe. Again relying on a cistern to fill the bowl, Cummings’s design used a sliding valve to seal the bottom of the bowl. When the contents were to be drained, a lever was pulled, and the valve slid back, sending the water and waste down the drainpipe.

• Water trapped in the S bend below prevented the characteristic stink of excreta from floating back into the room. This was a great step forward, but unfortunately, feces tended to get trapped in the
sliding valve, thereby clogging the mechanism and negating some of the toilet’s overall advantages. All of the basic components of the modern toilet were there, but they needed improvement.

- In 1778, Joseph Bramah offered the necessary enhancement by replacing the sliding valve with a self-cleaning, hinged flap valve. Bramah’s toilet needed to connect to a water source because it depended on a constant trickle of water to maintain sanitation conditions and seal out odor. The general design of this toilet dominated production until the 1930s.

- However, ultimately, a toilet is only as beneficial as the system to which it connects. The normal aversion for stench aside, little was understood about the true relationship between sewage and health in the late 18th and early 19th centuries. It was within this context that two of the most important examples of modern urban water and sewer systems were developed in Philadelphia and London. In both cases, disease played an important ill-founded role in their genesis.

**Philadelphia and London**

- In 1793, Philadelphia—the nation’s capital, a city of 45,000 inhabitants—was struck by yellow fever. That summer, 5,000 people died in the epidemic, causing a state of panic in which businesses and federal offices were abandoned as 17,000 people, more than a third of the city’s population, fled.

- The nearly universal opinion was that the disease was caused by miasma, noxious air that emanated from rotting organic material. After the epidemic, Philadelphia was primed to reclaim its status as the continent’s most sophisticated city.

- One of the city’s obvious shortcomings was its water supply. Seeking to remedy this defect, the city fathers approached architect and engineer Benjamin Henry Latrobe for his help in planning and constructing a central water supply system. The system that was established based on his design began to supply water in 1801.
• By 1810, the city’s need for water had outdistanced capacity. Frederick Graff—the superintendent of the waterworks, the son of a builder, and Latrobe’s former assistant—was commissioned to come up with a solution. Graff devised a system that raised water from a reservoir to a cistern by utilizing waterwheels to exploit the excess energy of the river to lift the water. He also improved on the earlier works by designing a system of iron pipes to carry the water throughout the city.

• The first outbreak of Asiatic cholera occurred in London in 1831; it would return four more times by 1854. The 1854 epidemic alone killed more than 10,000 Londoners. It was during this epidemic that a few individuals who had rejected the miasmatic theory of disease contagion found evidence of the real cause of cholera.

• Dr. John Snow, a local physician who had previously published a paper theorizing that cholera was a water-borne disease, saw this as an opportunity to test his theory. Snow plotted the addresses of the deceased on a map and noticed that most victims resided near the Broad Street public water pump. Furthermore, victims that did not reside near the Broad Street water pump could be shown with some certainty to have drunk from it.

• Snow examined a sample of water from the pump under his microscope and found particles that he believed were responsible for the spread of disease, although he could not prove this. Authorities doubted him, but agreed to remove the pump handle as an experiment.

• Deaths decreased sharply, but when a subsequent municipal report investigated Snow’s findings, it concluded “we see no reason to adopt this belief” about the origin of the disease.

• Even if that connection were unrecognized, there would prove to be another sufficiently repellent—and fortuitous—reason to act. The summer of 1858 brought to London the aptly named Great Stink. That summer, low water levels caused the metropolis’s accumulated
excreta to be carried not into the Thames, but only as far as the river’s margins, where it remained marooned. There it simmered, exposed to the extraordinarily high temperatures, steadily adding to the city’s fetid funk.

- With the miasmatic theory of disease holding sway, sheets or drapes were soaked in chlorine and hung over windows, but this had little effect on health or the sense of smell. Suddenly, with the evidence right under their noses, Parliament took just 18 days to rush through a bill to provide money for the construction of a massive new metropolitan sewer system—albeit for essentially the wrong reason.

- All of this incredible effort had been predicated on a false assumption: that cholera is carried not in the water, but in the air by a miasma. Purification of drinking water was only a secondary concern.

- In 1867, the second Reform Act granted urban working men the vote. The conjunction of greater political power and the self-evident benefits of public hygiene/health projects encouraged the working class to exert far greater pressure on politicians for more improvement projects. A long list of responsive legislation stretched over the next decade, including the following.
  - In 1866, the Sanitary Act mandated the appointment of town inspectors of water supply and drainage facilities.
  - During the 1870s, Birmingham Mayor Joseph Chamberlain spearheaded a series of urban improvement projects, including slum clearance and the construction of the municipal gas works and the water supply system.
  - The 1872 Public Health Act carved the country up into Health Authorities and required the appointment of Medical Officers and staffs.
○ In 1875, the Artisans’ Dwellings Act, which granted local authorities the power to purchase and demolish substandard housing, was passed.

○ In 1875, a second Public Health Act with compulsory requirements and enforcement authority was passed.

Modern Bathroom Plumbing

- Through the end of the 19th century, burgeoning public sanitation projects probably influenced a concomitant crop of developments in public and private lavatory technology. In the 1880s, the essential aspect of modern toilet design, the S bend, became an integrated element of the porcelain toilet bowl.

- The enterprising and fortuitously named Thomas Crapper sold millions of toilets with his name emblazoned on them. Public lavatories took on a grand appearance and offered all the modern conveniences, including urinals with a bull’s-eye situated to help the user avoid unpleasant splashes. The Unitas model was so ubiquitous in some areas of the world (such as Russia) that its name was adopted by the local language to have the generic meaning “toilet.”

- However, even though the turn of the 20th century saw the design of the modern flush toilet perfected, access to them was limited for much of the working class, even in the most developed areas of the world. In rural areas, sewer systems were rarely available.
In urban areas, when municipal systems made toilets a practical convenience, shared facilities became the norm.

- In urban Britain, courtyards behind “back to backs” featured three toilets for the use of as many as 70 people in the surrounding flats. Furthermore, being outside, they could be cold, dark, dirty, and rat infested. This was the standard provision for the British urban poor until the 1960s or 1970s.

**Suggested Reading**

Bryson, *At Home*.

Gibson and Wolterstorff, *The Fairmount Waterworks*.

Giedion, *Mechanization Takes Command*.

**Questions to Consider**

1. Why are the U-shaped trap and the hinged flap so important for the effective operation of the modern toilet?

2. While water and sewer systems are today housed in nondescript buildings in out-of-the-way parts of the city, why did the citizens of Philadelphia and London house their systems in architecturally distinctive buildings located in prominent places in the city?
Lecture 18: Batteries and Electric Generators

Both the battery and the generator provided a means for producing an electric current, and without them, we would not be able to enjoy the extraordinary number of electrical and electronic devices we have today. In this lecture, you will learn how these two inventions work and where they came from. Both exemplify an important theme in the history of technology in the 19th century: that inventors and scientists were fascinated by the idea that one form of energy could be converted into another.

The Battery

- In the early 19th century, electrical science expanded dramatically from the study of static charge to investigating what was then called dynamic electricity, or how charge could flow through a conductor like a copper wire. The key to this new research was the invention of the electric battery by Alessandro Volta in 1800.

- Volta came to invent the battery by way of a major argument he had with another Italian electrical scientist named Luigi Galvani. In the 1780s, Galvani was slowly skinning a frog at a table where he had been conducting experiments with static electricity by rubbing the frog’s skin.

- Galvani’s assistant touched an exposed nerve of the frog with a metal scalpel, and much to their surprise, the frog’s leg kicked as if it were still alive. Galvani realized that there must be a relationship between electricity and animation—or life. To describe the force that activated the muscles of his specimens, Galvani coined the term “animal electricity.”

- Volta repeated Galvani’s experiments and, at first, embraced animal electricity. However, Volta started to doubt that the phenomenon was caused by electricity intrinsic to animals. Instead, Volta
believed that the contractions depended on the metals Galvani used to connect nerves and muscles in his experiments.

- To prove his point, Volta decided to show that electricity could be generated by using two metals connected by a moistened disk. The disk was a substitute for Galvani’s frog leg.

- Volta found that he got particularly good results when he created a series of cups consisting of alternating copper and zinc plates, which were placed in either saltwater or diluted sulfuric acid. To make the device more compact, Volta soon replaced the cups with moist paper disks located between the alternating copper and zinc plates.

- Volta called this invention his “electric pile,” and to do this day, several European languages use the word “pile” to describe a battery or electric cell. Volta’s invention quickly became an international sensation.

- Several chemists began experimenting with the current produced by Volta’s pile and found that it could do wondrous things in terms of breaking down substances. For example, Sir Humphry Davy undertook a public subscription to raise funds so that he could build an enormous battery having 2,000 elements, and with the current from this battery, he used a technique known as electrolysis to discover new chemical elements: sodium, potassium, calcium, and chlorine.

- Sir Humphry also connected wires from the giant battery to two pieces of carbon; when he separated the two carbons slightly, the current created an incredibly bright light. This experiment led other inventors to develop the first electric lights, known as arc lamps.

- Nearly all modern batteries follow the model set by Volta and electric pile: There are two different electrodes—sometimes metal, sometimes not—and they are separated by an electrolyte. By choosing the right mix of electrodes and electrolyte, one can cause a chemical reaction that in turn produces an electric current that
flows when the two electrodes are connected by a wire.

- Through 19th century, inventors tried all sorts of different combinations of electrodes and electrolytes. Several combinations were successful and could be used to power early telegraph and telephone systems. However, all of these early batteries used a liquid electrolyte, which could spill and, hence, limited the application of batteries.

- As a first step toward a more reliable battery, the chemist Robert Wilhelm Bunsen (who also invented the Bunsen burner used in chemistry labs) created in 1841 a battery composed of a zinc electrode (forming the body of the cell) and a carbon rod at the center that formed the other electrode. For the electrolyte, Bunsen used a combination of two liquids: dilute sulfuric acid separated from the second electrolyte, chromic acid, by a porous ceramic wall.

- In 1886, Carl Gassner patented a new battery, known as a dry cell, that replaced the liquid electrolyte with a wet paste made of ammonium chloride and plaster of Paris. Gassner’s dry cell was more solid, did not require maintenance, did not spill, and could be used in any orientation. It provided a potential of 1.5 volts.

- It is also possible to have batteries in which the electrolyte is an alkaline rather than an acid, but of course, these cells use different combinations of metals for the electrodes. The first alkaline battery used a combination of nickel and cadmium and was invented in Sweden by Waldemar Jungner in 1899.
• Nickel-cadmium batteries have significantly better energy density than lead-acid batteries, but are much more expensive. Hence, they were not widely available in the United States until the 1960s.

• Another alkaline battery uses lithium for one of its electrodes. Research into lithium batteries dates back to 1912, but it was not until the 1980s that a practical lithium battery was perfected.

The Electric Generator

• While chemists and philosophers energetically debated what caused electricity to be produced in Volta’s pile, other scientists used it to conduct new experiments. Among these scientists was Hans Christian Oersted, who discovered in 1820 a relationship between electricity and magnetism.

• Oersted connected a wire to a Voltaic pile and then placed a magnetic compass under the wire. To his amazement, the compass needle was deflected only when he connected or disconnected the wire from the pile. Oersted’s experiments were repeated by André-Marie Ampere, who established that it was a flow of charge—a current—that was interacting with the magnetism of the needle and causing motion.

• In 1831, Michael Faraday, using a donut-shaped coil of wire and a bar magnet, demonstrated the laws of electromagnetic induction. Faraday showed that if one moved the magnet in and out of the donut, one could induce or generate a current in the donut coil. Conversely, if one sent a current through the coil, the magnet would move.

• However, to get either effect—to generate current or produce motion—the configuration of the coil and the bar magnet had to be at right angles with each other. In fact, the current induced would be at a third right angle, perpendicular to both the coil and the magnet. Engineers today refer to this as the right-hand rule.
• Faraday further realized the significance of Oersted’s observation that the compass needle was deflected only when the current was turned on or off; when the current was passing steadily through the wire, there was no deflection.

• Faraday hypothesized that both the magnet and the electric coil were each surrounded by an electromagnetic field (often depicted as a series of force lines) and that current or motion was produced when one of these fields was changing.

• When one turned the current on or off in Oersted’s wire, one energized or de-energized the field surrounding the wire, and this change interacted with the magnetic field surrounding the compass needle, causing the needle to swing.

• In utilizing Faraday’s discoveries about induction, experimenters soon added several new features to generators: First, to generate electricity, they wanted to use rotary motion—from a hand crank to a steam engine.

• Second, investigators came to desire electrical machines that produced a current similar to that which came from a battery; they wanted to work with a current that possessed a steady voltage, or what is called direct current. This fascination with direct current may have been fostered by the rapid development in the 1840s and 1850s of telegraph systems that sent signals by interrupting a direct current.

• To secure both of these features—rotary motion and direct current—electrical experimenters utilized a commutator. In both generators and motors, there are generally two sets of electromagnetic coils: a fixed set known as the field coils, or the stator; and a rotating set known as the rotor.

• A commutator is simply the device by which electric current moves into or out of the rotor. Introduced by Hippolyte Pixii in Paris in 1832, the commutator came to be an essential feature of direct
current motors and generators. Pixii’s commutator allowed electric generators to produce a direct current that was the same as that produced by a battery.

- Realizing that generators could produce lots of electricity that could be used in a variety of experiments and new applications, inventors and scientists began looking for ways to increase the output of these new machines.

- The first generators basically moved a coil of wire through a magnetic field created by a permanent magnet. Because it relies on permanent magnets, this type of generator is known as a magneto. Hence, the first thought toward producing more current was to increase the number of permanent magnets in the generator.

- Several inventors realized that you didn’t need the separate little magneto but that you could actually just draw a small portion of the electricity being produced by the main generator and use that small portion to excite the electromagnets of the generator. These new designs were called self-excited dynamic electric machines, or dynamos for short.

- The idea that a generator could be self-exciting was a major breakthrough, and this discovery was made simultaneously in 1866/1867 by S. A. Varley in England, Werner Siemens in Germany, and Moses Farmer in America.

- The final strategy that was developed in the effort to generate more current was to modify the arrangement of the coils of wire moving through the magnetic field. From the 1830s to the 1860s, electrical inventors had used individual bobbins of wire without really trying to maximize the amount of wire cutting the magnetic field at any given time.

- In 1867, Zenobe T. Gramme, a Belgian working in Paris, decided to come up with a better design for the rotor that ensured that lots of wire was cutting through the magnetic field. Gramme’s dynamo
produced more current without overheating and was quickly used in a variety of applications, especially electric lighting.

- Not to be outdone by Gramme, the Siemens brothers in Germany asked their lead designer, Friedrich von Hefner-Alteneck, to come up with an alternative. In response, von Hefner-Alteneck developed a drum-wound rotor. Compared to the Gramme ring, the drum-wound rotor was much easier to wind and, hence, cheaper to make.

- Both the Gramme ring and the drum-wound rotor significantly increased the output of electric generators, made electricity cheaper to generate, and thus paved the way for the application of electricity to a variety of new uses.

**Suggested Reading**

Pancaldi, *Volta*.

Schallenberg, *Bottled Energy*.

Schiffer, *Power Struggles*.

**Questions to Consider**

1. How do both the battery and generator illustrate the law of the conservation of energy?

2. Electrical inventions are often assumed to be “science based.” How does the development of the electrical generator challenge this assumption?
A theme that brings together several important 19th-century inventions is the idea of analog communications, in which information is stored or transported from one place to another by the creation of a representation that serves as an analog of the message. The camera, telephone, and phonograph are all examples, and as you will learn in this lecture, they all played a huge role in making information and knowledge widely available to millions of people. Moreover, because they were all owned or operated by individuals, they created the expectation that information can and should be shaped by individuals.

The Camera

- Since the 17th century, artists frequently began a painting by using a camera obscura to project an image onto paper or a canvas that they would then trace. Joseph Nicéphore Niépce was a French farmer and inventor who experimented with ways to capture an image without tracing. In 1826, Niépce coated paper with a light-sensitive chemical—silver chloride—placed it in his camera obscura, and produced the first photograph. Niépce called his process heliography, meaning “Sun writing.”

- To perfect heliography, Niépce worked with both his older brother Claude as well as Louis Daguerre, who had studied architecture, theater design, and painting. With Claude, Joseph had been working on an early form of internal combustion engine that they called their pyrégolophore.

- In 1837, Daguerre introduced a much-improved process using a copper plate coated with silver iodide. Daguerrotypes were simple to take and were highly stable images. Daguerre patented his process in England and elsewhere, and Daguerrotypes set off the first photography fad.
• One disadvantage of daguerrotypes was that the process created only one image, and it could not be copied. This problem was solved by William Henry Fox Talbot in England. By coating transparent paper with silver salts, Talbot found that he could create a negative image that in turn could be used to produce multiple positive prints. Talbot patented his process, calling it calotype, and promptly found himself embroiled in a patent dispute with Daguerre.

• Over the next few decades, photographers sought better photochemicals so that images could be taken with shorter exposure times and less light, and they experimented with coating metal and glass plates with these photosensitive emulsions.

• Photographs continued to be popular. In the 1860s, commercial photographers began offering carte de visite, or “card photographs,” and one could have a portrait taken and 25 cards made for as little as $2.50. During the American Civil War, photographers set up portable studios wherever the armies traveled, and thousands of soldiers sent cartes de visite home to their loved ones.

• In 1874, George Eastman began coating rolls of paper (and then celluloid film) and placed these rolls in a simple camera that he called the Kodak Brownie. Eastman made photography into a product that could be enjoyed by millions.

• Photography won an easy acceptance among people in the 19th century for several reasons. First, since the development of perspective painting in 15th century, people had become accustomed to viewing three-dimensional scenes in a two-dimensional painting. Because photographs used the same perspective technique, people could easily make sense of these new images.

• Second, the inventors of photography played up the idea that they had created new machines that produced “mechanical” reproductions of what was actually “out there.” Already feeling that machines were more important and more “objective” than other
human activities, people in the industrial revolution were inclined to see photographs as more real and credible than paintings.

**The Telephone**

- The telephone is an outgrowth of the development of the electrical telegraph that is technically a form of digital technology because it converts the message to pulses (dots and dashes) in order to transmit it.

- Developed by William Cooke and Charles Wheatstone in England and Samuel F. B. Morse in America, the electrical telegraph quickly evolved into a service used primarily by businessmen. In America, it was also controlled by the first monopolistic corporation, Western Union.

- One of the technical limitations of the Western Union network was that it could only send one message down a wire at a time. Because stringing wires was expensive, several inventors—including Thomas Edison and Elisha Gray—started working on the problem of multiplexing, or how to send multiple messages over a single wire.

- While Edison and Gray were professional telegraph inventors, the multiplexing problem attracted a novice inventor by the name of Alexander Graham Bell, whose father, Alexander Melville Bell, had developed an impressive system of symbols for recording the sounds found in any human language.

- Alexander Graham Bell experimented with a multiple-message telegraph of his own design. Based on his understanding of sound waves, Bell envisioned what he called a harmonic telegraph that consisted of numerous tuned reeds positioned over an electromagnet. Both the transmitter and receiver were identical and were connected by a battery circuit.

- If one spoke or sang in front of his theoretical harmonic telegraph, reeds tuned to the specific frequencies related to the incoming sound wave would start vibrating and, in turn, send an electric
current wave down the wire to the receiver. At the receiving end, these electric current waves would cause the appropriate reeds to sound, thus recreating the sound wave of the voice or song.

- While this harmonic telegraph served as a mental model and guided Bell’s thinking, he didn’t build the actual device because for a multiple telegraph, he was going to assign one message to each reed/frequency, so Bell only experimented with circuits containing two- or three-reed relays on each end.

- In June of 1875, Bell and his assistant Thomas Watson were experimenting with reed relays, hoping to send several messages simultaneously. Bell realized that he didn’t need a whole lot of reed relays to capture and transmit complex sounds—all he needed was one reed. Bell and Watson quickly built a prototype that demonstrated this idea in principle.

- In the spring of 1876, Bell received a patent for his telephone, and in 1877, Bell and Gardiner Hubbard, whose daughter Bell later married, started the American Bell Telephone Company.

- While Hubbard had envisioned the telephone as something that middle-class Americans would use for social purposes and to coordinate the activities of their homes and offices, the investors who took over American Bell in the 1880s found a larger and more lucrative market in selling telephones to businesses. To expand the business, AT&T started promoting consumer use of the telephone, encouraging people to make social calls.

- Further development of the telephone required innovations such as the switchboard (for connecting dozens and then thousands of users) as well as the electronic vacuum tube (for boosting signals for long-distance calls). Electronics allowed the telephone system to continue to grow in the 1930s and 1940s.
The Phonograph

- The phonograph was an outgrowth of the intense research that Edison and Bell conducted on the telephone. Western Union hired Edison and his team to develop an improved telephone for them.

- Edison became interested in how to convert sound waves not only into electric current waves, but also how a thin diaphragm converted sound into mechanical motion. In July 1877, while working on his telephone transmitter, Edison conceived the idea of recording and playing back telephone messages, and the phonograph was born.

- The first phonograph consisted of a grooved cylinder mounted on a long shaft with a screw pitch of 10 threads per inch and turned by a hand crank. Edison replaced the paraffin-coated paper with a piece of tin foil wrapped around the cylinder as a recording surface. The first phonograph had separate recording and playback mechanisms, but later designs combined them into a single unit.

- Edison patented his phonograph in 1878, but unable to figure out how to market this new invention, he soon lost interest and turned to developing his incandescent lighting system. In the meantime, Bell took up the phonograph, jealous that he had not thought of it first.

- Working with a skilled mechanic, Charles Sumner Tainter, Bell patented several improvements on the phonograph, including the
idea of using wax cylinders. Irritated that Bell would try and steal the phonograph from him, Edison threw himself into improving the phonograph during the summer of 1888. Working incessantly, Edison came up with new recording materials, new motors, and new diaphragms, and in 1888 and 1890, he took out 75 patents on phonograph improvements.

- Edison now thought that the phonograph could be used in a talking doll and as a dictating machine used in business, but neither application proved profitable. Instead, the most promising market was to create phonograph arcades, where people paid a nickel to listen to a song.

- Through the 1890s, the Columbia Phonograph Company promoted the idea of recording music and selling home phonographs, and the Edison Phonograph Company followed their lead. Focusing on the production of cylinders rather than picking good musicians and music, Edison drove down the cost of making cylinder records, and by 1901, he could make cylinders for 7 cents and sell them for 50 cents. But there were still more surprises in store for Edison and the phonograph—namely, disc records and the Victrola.

- As early as 1878, Edison had experimented with using disc records instead of cylinders, but he set discs aside because it was difficult to design a disc so that the record needle passed over the surface at the same speed.

- Recognizing that disc records would be easier to manufacture and could hold more music, Emile Berliner, an inventor from Washington DC, developed a commercial disc machine that he called a gramophone.

- Disc records proved popular, and in 1901, one of Berliner’s associates, Eldridge Johnson, launched the Victor Talking Machine Company, whose Victrolas were immediately recognizable by the large morning glory–shaped horns that they used to amplify the acoustic signal.
• The Victor Company came up with two important innovations: It produced machines that looked like fine furniture by folding the horn inside the case, and it sought out great singers like Enrico Caruso and promoted them heavily—dubbing them “stars.”

• Just as Bell had aroused his competitive spirit in the 1880s, the Victor Company got Edison moving on a disc phonograph around 1910. Edison focused on a higher-quality record surface and on recording music with greater fidelity.

• While Edison’s records were technically superior, they were incompatible with the competitor’s machines. In addition, Edison refused to promote “star” performers and insisted on recording only those whose voice he personally considered superior. As a consequence, the Edison phonograph companies were never able to get ahead of Victor, and Edison exited the phonograph business in 1929, two years before he died.

Suggested Reading

Bruce, Bell.


Lubar, InfoCulture.

Questions to Consider

1. What does it mean to say that the camera, telephone, and phonograph are all forms of analog communications?

2. Why might it be said that Bell’s invention of the telephone was a love story?

3. Why did Edison prefer to use cylinder records in his phonograph as opposed to the disk records that were popularized by the Victor Company?
Electric power systems played a profound role in shaping the economy of America and other industrial nations by making power cheaper and more widely available. In this lecture, you will learn that the evolution of electric power came in two phases: Thomas Edison developed a system of incandescent lighting in the early 1880s using direct current, and in the late 1880s, Nikola Tesla invented an alternating current system with motors that allowed power to be transmitted over longer distances.

**Edison and Direct Current**

- While many are taught that Thomas Edison single-handedly invented electric lighting in 1879, there was actually electric lighting before Edison came along. The first electric light was the arc light, invented by Sir Humphry Davy in 1807.

- Inspired by Volta, Davy had built a huge electric battery, and to demonstrate its power, he connected the terminals of the battery to two carbon rods. When he separated the carbons by a tiny distance, the current jumped the gap but, in so doing, gave off an incredibly bright light.

- Over the next 50 years (1810s–1860s), a variety of inventors worked to develop arc lamps with electromechanical regulators that maintained the exact gap needed between the carbons to create the bright light.

- The possibility of using arc lights to illuminate streets and large buildings spurred other electricians to improve the generator. Zenobe T. Gramme introduced a dynamo with a better armature, and he promptly used this dynamo to power an arc light.

- In 1876, with backing from the Telegraph Supply Company in Cleveland, Charles Brush designed a direct current generator that
could power four arc lights in a series circuit. Brush’s powerful lights were used to illuminate streets, factories, and retail stores.

- Because most users could not afford to purchase a complete arc lighting system, entrepreneurs in different cities followed the lead of the California Electric Light Company in San Francisco, which set up the first central utility station in 1879 for selling lighting as a service.

- Arc lighting was great for illuminating streets and large buildings. However, arc lighting was not especially useful if one wanted a smaller, softer electric light. Recognizing this, Edison decided in 1878 to drop his work on the telephone and phonograph and plunge into a field he knew nothing about—electric lighting.

- To create a smaller lamp, Edison decided to take advantage of incandescence: When an object is heated, it begins to glow, and once it reaches a critical temperature, the object not only glows but can give off light. Incandescence is when the heating element in your toaster glows orange.

- To take advantage of incandescence, Edison decided in September 1878 to experiment with platinum filaments. However, platinum is a rare and costly metal. Moreover, platinum also has a low electrical resistance, meaning that his distribution system would need large and expensive copper-wire conductors.
• Fortunately, Edison realized that he could overcome the need for large copper distribution mains by increasing the resistance of each lamp and putting them in parallel circuits. The challenge now became finding a high-resistance filament. For several months, Edison and his team tried dozens of materials, only to find that the lampblack carbon Edison had been using in his telephone transmitters was the idea material.

• In October 1879, Edison and his staff conducted their first successful experiments with a filament made from a piece of carbonized thread. By putting the carbon filament in a vacuum, they were able to bring it to a high state of incandescence because there was no oxygen to cause the filament to burn.

• To commercialize his incandescent lamp, Edison designed an entire electrical system, which he modeled after the gas lighting systems used in large cities, including central stations, underground conductors, meters, and lamp fixtures. In addition, Edison also had to design an electrical generator and the network it powered.

• Edison installed his first central station in lower Manhattan in 1882. His system was most efficient and economical within a square mile of the central station. Edison was able to increase the distance over which his system could be used by the addition of a third neutral wire.

**Tesla and Alternating Current**

• In the early 1880s, Edison found himself competing with Charles Brush, Elihu Thomson, Edward Weston, and other inventors who devised their own incandescent lighting systems.

• However, the biggest challenge facing Edison was the fact that his system was only economical when it was installed in towns and cities where there was a densely populated downtown; in those situations, there were enough customers in a given area that could offset the cost of laying the copper mains required for his direct current system.
• In America, there were numerous towns that had the money for electric lighting, but the population was too spread out to warrant installing an Edison system. Recognizing this larger market, George Westinghouse decided to develop an alternating current lighting system.

• Thinking of Ohm’s law, Westinghouse reckoned that if he raised the voltage (on the order of 800–1,000 V) used to transmit the current, he could reduce the size of copper mains. However, because he didn’t want to bring 1,000 V into people’s houses, Westinghouse had his engineers borrow a device invented in Europe, the transformer, which they used to step down the voltage from 1,000 V to 110 V.

• In 1887, alternating current looked very promising to electrical engineers, but they soon realized that they had an economic problem on their hands. Ideally, an alternating current system should cover an entire city, but that meant that the power plant and related wiring would require a significant investment, and to offset that investment, it would be good if the plant could deliver electricity 24 hours a day, 7 days a week.

• However, to do that, the electrical engineering community realized that it would need a motor that would consume power during the day—a motor that could be used in streetcars, factories, elevators, and all sorts of applications.

• It was at this critical juncture that a remarkable inventor named Nikola Tesla turned up with just the right invention: an alternating current motor. In 1882, he envisioned the idea of using a rotating magnetic field in his motor. Up to this time, inventors had designed direct current motors in which the magnetic field of the stator was kept constant and the magnetic field in the rotor was changed by means of a commutator.

• Tesla’s insight was to reverse standard practice: Rather than changing the magnetic poles in the rotor, why not change the magnetic field in the stator? This would eliminate the need for the
sparking commutator. Tesla envisioned that as the magnetic field in the stator rotated, it would induce an opposing electric field in the rotor, thus causing the rotor to turn. Tesla surmised that the rotating magnetic field could be created using alternating current instead of direct current, but at the time, he did not know how to accomplish this.

- In September 1887, Tesla discovered that he could produce a rotating magnetic field by using two separate alternating currents fed to pairs of coils on opposing sides of the stator. In modern engineering parlance, we would say that the two currents are 90 degrees out of phase with each other, and Tesla’s motor would be said to be running on two-phase current.

- Tesla filed a series of patents broadly covering alternating current motors using the principle of a rotating magnetic field. Engineers from the Westinghouse Company inspected Tesla’s motor, and George Westinghouse purchased Tesla’s patents for $200,000.

- Westinghouse hoped that one of Tesla’s motor designs could be used to run streetcars. However, because Tesla’s best motor required two alternating currents and four wires, it was not possible to add this motor to existing single-phase alternating current systems. One would need to install new two-phase generators.

- Although Tesla had developed a number of two-wire motors, these designs ran best on currents of 50 cycles or less; at the time, the Westinghouse single-phase systems were using 133 cycles so that consumers would not complain about their incandescent lamps flickering.

- Westinghouse engineers were stymied as to how they could combine lights and motors onto a single network. Led by Charles F. Scott and Benjamin G. Lamme, the engineers at Westinghouse eventually solved these problems by modifying Tesla’s motors and developing a new alternating current system using 60-cycle current with either two or three phases.
The Battle of the Currents

- By the late 1880s, Edison General Electric (GE), the Westinghouse Electric and Manufacturing Company, and the Thomson-Houston Electric Company had emerged as the key players. Racing to install central stations in cities across America, these rivals used a variety of tactics.

- While Westinghouse pioneered the use of alternating current, Thomson-Houston focused on helping fledging utilities raise the money needed to build new power stations. Drawing on the fortune he had made by inventing the railroad air brake, George Westinghouse often underbid his rivals in competing for contracts.

- In 1892, the struggling Edison GE Company was taken over by the Thomson-Houston Company in order to form General Electric. While Westinghouse held the lead in alternating current engineering, GE dominated in finance, incandescent lamp manufacture, and the development of efficient steam turbines used to turn generators.

- The Westinghouse Company dramatically demonstrated its alternating current system first by providing power to thousands of lights at the 1893 World’s Fair in Chicago and then by supplying generators in 1895 for the hydroelectric station at Niagara Falls, which transmitted large amounts of power over 25 miles to factories in Buffalo.

- With Niagara, the basic pattern of the American electrical industry was established for much of the 20th century: Alternating current power was generated and distributed on a massive scale by investor-owned utilities and was used by a growing number of industrial and residential customers.

- Because the capital costs of building new plants is so high and the marginal profits in selling power is so low, utilities have generally sought to build ever larger networks—first across cities, then entire states, and eventually regions covering multiple states.
• As demonstrated first by Samuel Insull at Commonwealth Edison in Chicago, a utility could increase its profitability by expanding its service territory and diversifying its service load. Commonwealth Edison soon became the sole supplier of electricity in the region and, hence, a monopoly.

• To preempt the government from trying to break up his monopoly, Insull persuaded the Illinois legislature to create a commission for regulating utilities. Other states followed Illinois, and for most of the 20th century, investor-owned utilities avoided being attacked as monopolies by ceding the power to set rates to state regulatory commissions.

Suggested Reading

Carlson, Tesla.

Friedel and Israel, Edison’s Electric Light.

Hughes, Networks of Power.

Questions to Consider

1. How is Edison’s invention of the incandescent lamp a story of finding the right material?

2. Why was there a limited market for Edison’s direct current lighting system? How did alternating current allow George Westinghouse and Nikola Tesla to overcome these limitations?

3. What prompted Harold Brown and the managers of the Edison General Electric Company to launch the battle of currents against Westinghouse?
In this lecture, you will learn about the invention of new ways of selling goods to people—namely, new arrangements for retailing goods. You will learn that by the late 19th century, businessmen had invented three new ways to shop: department stores, mail-order catalog companies, and retail chain stores. Along the way, you will learn the origins of several venerable institutions that are part of the American business and cultural landscape, such as Macy’s, Sears, and Woolworth’s, and consider their importance in history.

Shopping in History

- Even though we often trivialize shopping as a frivolous activity, it’s nonetheless the vital component in any economy. Shopping is the final step in a long sequence of activities that move goods from production to consumption by individuals and families.

- For thousands of years, individual consumers met the actual producers of goods at markets or bazaars, often held weekly or daily in the larger towns. There were not only markets in ancient Mesopotamia and imperial Rome, but also in medieval and early modern European cities.

- Beginning in the 14th century, in European cities, some entrepreneurs began specializing in the selling of particular goods such as clothing, books, or jewelry. Goods such as these often commanded a high price and warranted entrepreneurs to specialize in finding suppliers, to maintain an inventory, and to rent space where customers could examine the merchandise.

- Retailing—which comes from the French word *retailer*, meaning “to cut off, pare, or divide”—refers to the idea that entrepreneurs were focusing on the sale of a small quantity of goods. They were neither manufacturers nor wholesale merchants who concentrated
on moving large quantities of goods. Retail shops came to America with the early settlers and could be found in the major cities and larger towns.

- For much of the 19th century, Americans purchased the goods they needed from two basic retailers: If they lived in the city, they visited shops that specialized in one particular line of goods (for example, clothing, food, books, or jewelry), while if they lived in the country, they relied on the general store, which sold the wide range of goods needed for farming, for example.

- However, just as some industrialists concentrated on manufacturing large quantities of products at low prices, other businessmen created new arrangements for mass distribution: department stores, mail-order catalog companies, and retail chain stores. Together, these new arrangements began to transform Europe and America into consumer societies.

**Department Stores**

- The first new marketing arrangement aimed at reaching a broad audience was the department store. The idea behind a department store was that it carried a wide variety of goods (organized into sales departments), making it convenient for the shopper to have to only visit one store.

- To further attract shoppers, department stores bought a large volume of goods from manufacturers cheaply and, in turn, offered these goods at low prices. The department store made its money not on a large markup (or profit) on each sale, but by selling numerous items to many customers with a small markup.

- Among the earliest department stores were Bennett’s of Irongate—dating from 1734 in Derby, England—which was an early textile center, as well as Kendall’s of Manchester, which began as Watts Bazaar in 1796. The grande dame of English department stores, Harrods, was founded by Charles Henry Harrod in Southwark, London, in 1824 and focused first on linens and then on groceries.
• The first retailer to practice the idea of selling a variety of goods in large volume was Alexander T. Stewart, who opened his Marble Dry Goods Palace in New York City in 1848. Stewart offered European merchandise at fixed prices, an innovation that was attractive to middle- and upper-class women shoppers who did not enjoy haggling over prices with shopkeepers. To further attract female customers, he also offered special sales and fashion shows.

• In 1858, Rowland H. Macy imitated Stewart and opened a “fancy dry goods store” in New York. During the 1860s, Macy expanded to include drugs, china, glassware, home furnishings, books, and toys at his store.

• Meanwhile, in Philadelphia, a men’s clothing retailer, John Wanamaker, was creating his own version of the department store. In 1876, he purchased an old Pennsylvania Railroad freight building and remodeled it as his Grand Depot. There, Wanamaker offered an enormous variety of goods at guaranteed low prices.

• As department stores were built in other cities, they followed Wanamaker’s lead and positioned themselves downtown near transportation lines. By the start of the early 20th century, nearly every American city had its own department store that reflected the geographic location and social composition of that city.

• Department stores not only facilitated the distribution of manufactured goods, but they also helped shape the social landscape in America: Catering to women, they were one of the few places women could visit safely on their own in the late-19th-century city; and department stores were very much the arbiters of middle-class taste in America, providing a mix of both practical items as well as goods that signaled the aspirations of the middle class.

Mail-Order Catalog Companies
• While the department store began in Europe and migrated to America, a second retailing invention—the mail-order catalog company—was a uniquely American innovation.
• Just as the railroads permitted farmers to ship their crops to be processed and consumed in cities, the expansion of the railroads permitted entrepreneurs to develop the mail-order catalog company. Recognizing that the growth of the railroads would allow him to ship goods to farmers across the country, Aaron Montgomery Ward founded a mail-order business in 1872.

• Ward believed that by eliminating intermediaries, he could cut costs and offer a wide variety of goods to rural customers, who would order goods by mail and pick them up at the nearest train station. To take full advantage of the emerging rail network, Ward located his operations in Chicago, the major rail hub of the Midwestern states.

• To entice farmers to order goods, Ward issued catalogues filled with woodcut illustrations of each and every item for sale, and he assured his customers that they could return any item for a full refund. Ward included pictures and signatures of his managers and buyers, and he made certain that the company responded with a hand-written letter to every inquiry and order. These practices proved highly profitable, and orders poured in.

• The success of Montgomery Ward stimulated the development of other mail-order companies, including Sears, Roebuck and Company in 1887. The central challenge for both of these companies lay not in manufacturing products to sell through their catalogues but, rather, in devising ever-more efficient ways of fulfilling orders.

• The key was to increase the speed by which goods ordered by customers moved from the warehouse to the mail train that delivered the orders. To increase speed, both companies built huge warehouse and distribution centers in Chicago filled with conveyor belts and hundreds of clerks.

• Following a precise schedule, each incoming order was divided into categories, and each individual department covering a category of goods was typically given 15 minutes to send to the assembly room
the articles required to fill that order. If the articles didn’t arrive in the assembly room by the allotted time, the order was shipped without the items, and the delinquent department was fined the cost of the extra shipment.

- In filling millions of orders, both Sears and Montgomery Ward provided ordinary citizens with the chance to enjoy a wide range of manufactured goods and thereby feel connected to the larger industrial and cultural trends shaping American society.

Retail Chain Stores
- The underlying idea behind chain stores was to have a large number of stores sharing central purchasing, advertising, and accounting departments. Buying on behalf of all the stores in the chain, the central office could negotiate favorable deals from manufacturers for large quantities of goods. Like department stores, chain stores made their profits by turning over huge quantities of goods with a small markup on each.

Retail stores were just one of the types of stores that were invented to help with the mass distribution of goods.
• The first chain stores sold groceries and served regions. In 1859, George Huntington Hartford and George F. Gilman organized the Great American Tea Company; they bought cargoes of tea from incoming ships and sold it directly to customers, thus eliminating middlemen.

• In 1869, they changed the name to the Great Atlantic & Pacific Tea Company (A&P) to celebrate the completion of the transcontinental railroad in 1869. In the 1880s, the business was taken over by Hartford’s sons, who expanded from tea into selling coffee, cocoa, sugar, extracts, and baking powder.

• Unlike the existing traditional groceries stores that offered services such as home deliveries and credit, A&P kept its costs low by emphasizing a policy of cash-and-carry rather than extension. As it built more stores, A&P integrated backward by manufacturing some food products under their own brand, allowing them to cut costs further.

• The success of A&P was imitated not only by other grocery companies but in other areas as well. In the early 1880s, Frank W. Woolworth opened seven variety or “dime” stores in southeastern Pennsylvania that offered low-priced nonperishable goods. In 1902, J. C. Penney started with a single store in a small town in Wyoming in which he sold inexpensive dry goods. Charles R. Walgreen, a Chicago pharmacist, founded a chain of drugstores in 1909.

• At first glance, it might be easy to conclude that Walmart—the largest retailer in the world and the largest private employer in the world (with two million employees)—must have done something remarkably different than the stores like A&P or Woolworth’s that have fallen by the wayside. In reality, the secret of Walmart is to follow the same formula of earlier chain stores, only more aggressively and on a global scale.

• More than the department store and the mail-order catalog company, the retail chain store was able to adapt to changing trends of the
20th century. As the number of small- and medium-sized towns proliferated in Midwestern and Western states, the chains were able to move into towns that lacked the population needed to support a large department store.

- Moreover, as streetcars and automobiles permitted people to move to the suburbs of cities, chain stores also moved to the new neighborhoods. Recognizing the trend toward suburban shopping, both Sears and Ward’s began building their own retail stores in the late 1920s.

- However, having developed a network for efficiently purchasing and distributing goods nationally, retail chain stores came to be—and remain—the dominant arrangement by which Americans shop and purchase manufactured goods.

Suggested Reading

Boorstin, *The Americans*.

Chandler, *The Visible Hand*.

Questions to Consider

1. Why are department stores an essential part of the story of industrialization?

2. What business strategies does Walmart use that were pioneered by A&P and Woolworth’s?
Motion Pictures
Lecture 22

As urban populations grew at the end of the 19th century, ordinary people demanded new forms of entertainment, and entrepreneurs employed new machines in response. Curiously, each new invention for mass entertainment involved very similar challenges. From the motion pictures to the newest forms of popular entertainment, inventors have had to tackle three interrelated problems: building devices for capturing and storing information, creating new forms of content, and devising new ways of distributing the content. To explore these three challenges, this lecture will focus on Thomas Edison and his experience with inventing and promoting motion pictures.

Inventing by Analogy

- Edison began working on motion pictures in 1888. For him, motion pictures began as an analogy with the phonograph. If one could use a machine to record sound, Edison reasoned, why not record motion using phonographs in some way? Edison referred to his invention as the “kinetoscope,” a term he concocted from the Greek word for motion, kinesis.

- Edison’s thinking about the potential for moving pictures was stimulated by a meeting in February 1888 with the photographer Eadweard Muybridge, who may have told Edison about how he had mounted some of his photographs in a zoetrope in order to create the illusion of motion. Intrigued, Edison ordered a set of Muybridge’s photographs. From Muybridge, Edison learned that motion could be recorded in a sequence of photographs.

- Edison first outlined his mental model of the kinetoscope in his October 1888 patent caveat. Reasoning by analogy from the phonograph, he proposed to replace the sound grooves of the record cylinder with a continuous spiral of tiny photographs.
Having conceptualized the kinetoscope, Edison turned to developing it as a physical artifact. To do so, he assigned the project to one of his experimenters, William K. L. Dickson, a young Scotsman who was knowledgeable about photography.

For the first machine, Dickson took a series of miniature daguerreotypes on tiny silver plates. These were then glued to the surface of a blank phonograph cylinder. Unfortunately, these images were indistinct when viewed through the microscope objective.

Bothered by the quality of the cylinder microphotographs and the problem of getting a lightweight cylinder, Dickson decided to experiment with a tachyscope, which was invented by a German named Ottomar Anschuetz and consisted of a large wheel on which animal motion pictures were mounted along the periphery. Like the cylinder kinetoscope, the wheel was rotated rapidly, and when a picture passed by an aperture, it was illuminated momentarily by an electric light.

Using copies of the Muybridge photographs that Edison had purchased, Dickson constructed a tachyscope in December 1889 and soon obtained positive results. However, not satisfied with merely recording motion, Dickson made a few more changes. Instead of having the viewer peer at moving images through an aperture, Dickson magnified and projected them on a screen. Dickson also connected the tachyscope with a phonograph so that his projections could speak.

Dickson demonstrated his projecting tachyscope to Edison in March 1890. However, the projected image had its limitations; years later, Edison complained that it flickered badly. Even Dickson himself admitted that the projected image was small (perhaps four by six inches) and limited by the power of the arc lamp used in the projector. Nevertheless, Dickson did demonstrate that motion pictures could be projected.
• With the projecting tachyscope, Dickson made his most original contribution to the development of Edison’s motion pictures. In the spring of 1890, however, Edison was not impressed with projected motion pictures and ordered Dickson to drop this line of work.

• At this time, Edison had not developed the familiar horn for his phonograph (which amplified the sound) but instead had listeners use individual ear tubes. In Edison’s mind, the phonograph had to be connected to each user, and consequently, he may have assumed that the same had to be done with the kinetoscope by means of an individual eyepiece or aperture.

• Significantly, this individual user arrangement with the phonograph had already led to one marketing scheme; in some cases, Edison had sold phonographs to small businessmen who established phonograph parlors, where patrons paid to listen to a song or two. Edison marketed the kinetoscope for use in similar parlors, and perhaps as early as 1890, he was already considering this market arrangement.

The Move to Strip Film
• To develop the kinetograph, or camera, Dickson began in early 1891 by cutting a large sheet of celluloid film into narrow strips and gluing the ends together. Along one edge, Dickson initially cut a series of notches that engaged a gear wheel, which advanced the film behind the lens in the camera and was driven intermittently by a clock escapement. This arrangement soon proved unsatisfactory because the gear rapidly chewed up the film.

• In response, either Edison or Dickson found a solution in an old telegraph instrument. In an automatic telegraph device designed by Charles Wheatstone, Morse code messages were fed into the transmitter by a punched paper tape. In order to advance the tape, Wheatstone had used perforations along one edge, which engaged the teeth of a small sprocket wheel.

• With the help of one of the lab’s machinists, Dickson adapted this idea to the kinetoscope, and a new camera was constructed
in the spring of 1891. After using one row of perforations along the bottom of the film, Dickson soon discovered that the wider films required perforations on both edges in order to advance the film smoothly.

- To complement their new camera (or kinetograph), Dickson and Edison fashioned a new viewing machine, or kinetoscope. Following Edison’s phonograph mental model, the new machine was a peep-show affair in which a single viewer watched the images through a lens mounted on the top of a large wooden box. Inside the box, the film was arranged as a continuous loop and mounted on a series of rollers.

- To provide power for moving the film, Dickson and Edison used a battery-powered motor. For viewing, the film was advanced by the same mechanism found in the camera. Each image was rendered independent in the viewer’s eye by a continuously rotating disk shutter with a large curved aperture. Illumination was provided by an incandescent lamp.

- From 1891 to 1896, Edison manufactured and promoted the basic configuration of the kinetograph and kinetoscope. Edison continued to use the phonograph analogy as his mental model to develop the motion-picture business.

- Kinetoscopes were assembled in the Edison Phonograph Works, employing the same men, machinery, and techniques used to produce phonographs. To provide national distribution, he copied his marketing scheme for the phonograph and organized a network in which entrepreneurs purchased a franchise to sell kinetoscopes in a particular state or territory.
These businessmen purchased kinetoscopes from Edison, and in turn, they sold them to small businessmen who established kinetoscope parlors patterned after phonograph arcades. In these parlors, patrons paid to watch a short film through the peephole; to accommodate this practice, Edison had one of his experimenters adapt the coin mechanism from the phonograph to fit the kinetoscope.

**Projecting Movies and Nickelodeons**

- In the mid-1890s, the Edison kinetoscopes did well for several years as the latest entertainment fad, but business soon slowed as the public grew accustomed to the short films. In response, other inventors in both Europe and America took up Edison’s motion-picture technology and improved upon it.

- In particular, several inventors, including Auguste and Louis Lumiere in France, developed a machine for throwing images up onto a screen so that they could be enjoyed simultaneously by a number of people. Despite their technical success, the Lumiere brothers declined to sell their camera or projector to other filmmakers and instead devoted themselves to developing color photography.

- Edison finally introduced a projector, which he called his vitascope, in 1896 only after being pressured by his own kinetoscope agents. Significantly, Edison did not develop this device in his lab, but instead purchased the patent rights to a projector from another inventor, Thomas Armat. Dickson left the Edison laboratory in 1897 and promoted his own version of a projector, which he called the mutoscope.

- Initially, projected films were incorporated into the vaudeville performances and were shown between acts. However, before long, another set of entrepreneurs recognized the value of opening up small theaters dedicated to showing movies continuously.

- Harry Davis and John P. Harris are generally credited with this innovation, which began as they opened their small storefront
theatre in Pittsburgh in 1905. They called this new theater the nickelodeon, joining “nickel” (the price of admission) with the Greek word for an enclosed theater, *odeon*, which was also the name of a famous 18th-century theater in Paris (Odéon).

- Although they attracted both middle- and working-class audiences, nickelodeons were regarded by many as disreputable places frequented by immigrants and the poor. Nevertheless, nickelodeons sprang up quickly all over America, doubling between 1907 and 1908 to around 8,000.

- Edison’s companies did well in the nickelodeon era. Under the leadership of patent attorney Frank L. Dyer, Edison set up the Motion Picture Patents Company, which used Edison’s early motion-picture patents to try and require everyone using a motion-picture camera or projector to secure a license from them. In addition, Edison’s organization produced films.

- Because nickelodeons showed several films every day and changed their offerings frequently, they created a huge demand for films and stimulated the growth of the film industry with hundreds of movie companies.

**Feature Films, Movie Palaces, and Hollywood**

- By the 1910s, Americans had become accustomed to going out to the movies, and film directors and nickelodeon owners began experimenting with new ways to keep the audiences coming back.

- While directors wanted to make longer movies because they could tell more elaborate stories, nickelodeon owners wanted longer movies so that they could collect more revenue by raising ticket prices from a nickel to a dime. These two forces prompted the development before 1915 of multi-reel feature films. As the revenues increased, nickelodeon owners scaled up the size of movie houses, making them into elaborate movie palaces.
• Because feature films were more expensive to make, film companies looked for ways to save on costs, and one way was to try and avoid paying licensing fees to Edison’s Motion Picture Patents Company.

• Figuring that it would be harder for Edison’s New Jersey-based company to track them down in California, many of the fledging film companies relocated in the early teens to the Hollywood district of Los Angeles. In 1911, Hollywood was second only to New York in motion-picture production, and by 1915, the majority of American films were being produced in the Los Angeles area.

Suggested Reading

Carlson, “Artifacts and Frames of Meaning.”

Carlson and Gorman, “Understanding Invention as a Cognitive Process.”

Lubar, InfoCulture.

Questions to Consider

1. What does it mean to say that Edison invented motion pictures by drawing an analogy from the phonograph? What other examples of invention by analogy have you encountered in this course?

2. Some historians credit Edison’s assistant, William K. L. Dickson, as being the “true” inventor of motion pictures. How much credit do you think Dickson should get?

3. What role did the creation of nickelodeon theaters play in the development of motion pictures?

4. Why did the film industry move from New York to Hollywood in the 1910s?
Inventions have reshaped how we travel, what we eat, and how we entertain ourselves. In this lecture, you will learn about another important area where inventions have reshaped daily life, medicine, and, more particularly, surgery. In the second half of the 19th century, surgeons and doctors introduced a host of technological innovations to make surgery safer. These innovations can be grouped around the three major risks confronting surgeons and patients: pain, bleeding, and infection.

**Pain**

- Before the invention of anesthesia, surgery was traumatically painful, and surgeons had to be as swift as possible to minimize patient suffering. For centuries, physicians and patients have searched for various remedies to minimize pain, and for surgery, they sought a way to put the patient into a suspended state (“sleep”) without killing him or her.

- Herbal potions—based on hemlock, mandrake, and other plants—were often quite poisonous and were best smelled rather than eaten. Among the other approaches tried were alcohol, opium, and even knocking the patient out with a swift blow to the jaw. Needless to say, all of these have drawbacks.

- During the 1700s, Anton Mesmer developed sophisticated methods of hypnosis, which some doctors hoped could be used to put patients into a state where they were unaware of pain, but they were not able to do so with any consistency.

- Instead, hypnosis, via Sigmund Freud, went on to play an important role in psychiatry. Such was the state of affairs that prompted the invention of anesthesia in the 1840s in Europe and America.
• Over the previous several decades, chemists had discovered how to isolate a variety of gases, including oxygen, hydrogen, nitrogen, nitrous oxide, and vapors of diethyl ether. In the spirit of experimentation, these men of science—including both Joseph Priestley and Sir Humphry Davy—often inhaled these gases, thinking that they might have health benefits, but in the case of nitrous oxide and ether, they found that the gases made them feel giddy and carefree, and nitrous oxide became known as “laughing gas.”

• Because surgeons prided themselves on their swift ability to execute complicated procedures and because they took the moral view that pain was God’s punishment for sin, traditional doctors were not especially interested in using laughing gas or ether in their practices.

• Dentists, however, were generally self-trained in early 19th-century America and were keen on developing ways to attract patients by making their procedures less painful. One pair of Boston dentists keen on attracting new patients were Horace Wells and William Morton, partners in “mechanical dentistry,” in which they specialized in replacing rotting teeth with dentures.

• In 1844, Wells had laughing gas administered to him, and while he was under, one of his dental students extracted a tooth. Wells subsequently tried to convince other doctors and dentists to use nitrous oxide in their operations, and when he failed, he became depressed, addicted to sniffing ether, and killed himself in 1848.

• His partner, Morton, hoping to make the transition from being a dentist to being a medical doctor, signed on as private pupil of Dr. Charles Thomas Jackson, who introduced Morton to “toothache drops” that could be applied topically to teeth before extraction. A key ingredient in the drops was ether.

• Determined to have a painkiller to use in his dental practice, Morton took two steps: First, he decided that he could get a more controlled effect by having patients inhale ether vapors. Second, he decided that he needed to purify his ether vapors to a high level, leading him to
create what he called “Letheon gas.” In 1846, Morton used his new gas and inhalation apparatus on a patient while a surgeon removed a large tumor from the neck while the patient rested quietly.

- Morton patented his Letheon gas, but in doing so, he was challenged by his old mentor, Jackson, who insisted that he had come up with the idea of using ether as an anesthetic. Morton died in 1868, still fighting with Jackson over who was the true inventor of ether-based anesthesia.

- Ether is poisonous and highly flammable, and it often induced vomiting in patients after surgery. These complications prompted the Professor of Midwifery at the University of Edinburgh, James Young Simpson, to investigate alternatives.

- After inhaling acetone, benzene, benzoin, and other reagents, Simpson found in 1847 that a dense, colorless liquid, chloroform, induced a sense of euphoria while depressing the central nervous system.

The first appendectomy was performed in Iowa in 1886, and the first heart surgery was performed in Germany in 1896.
• Although surgeons continued to question the efficacy and safety of anesthesia—for which there were good reasons to do so—they also challenged anesthesia because anesthesia meant a redefinition of their profession; rather than being the "armed savage" who overpowered the patient and performed the necessary procedure, surgeons now needed to be scientifically trained and to develop more humane bedside manner.

• Nevertheless, because anesthesia came to be valued by the growing number of middle-class patients, it came to be an accepted part of medical care in the middle decades of the 19th century.

• Perhaps the cultural turning point for anesthesia came in 1853, when chloroform was administered by Dr. John Snow to Queen Victoria during the birth of her 8th child. And unlike Wells, Morton, and Jackson who all died penniless, Simpson—the inventor of chloroform—died rich and was knighted by the Queen.

• Besides inhalation, anesthesia can be administered by injection. Beginning in the 1870s, physicians tried using barbiturates that were injected intravenously, but the first really effective intravenous anesthetic, evipan, did not appear until 1930s. For minor operations (such as those in dentistry), cocaine was topically administered; because cocaine is highly addictive and can be toxic, chemists developed artificial substitutes, such as lignocaine and novocaine.

• Because it is essential to track the patient’s state while under anesthesia, the anesthesiologist relies on the stethoscope (invented in 1816) to listen to the heartbeat. Additional monitoring devices were introduced into the operating room in the mid-20th century, including the electrocardiograph (EKG), blood pressure cuff, pulse oximetry, and, most recently, brain-wave monitors.

**Bleeding**

• Once the operation is underway, a surgeon has to deal with numerous vessels and arteries to prevent the patient from bleeding. From ancient to modern times, the usual method of sealing wounds
by searing them with a red-hot iron often failed to arrest the bleeding and caused patients to die of shock.

- Another approach, first described by the Roman physician Galen, was to tie off the vessels with a thread, a technique known as ligature. This technique was forgotten during the Middle Ages but was revived by the French surgeon Ambroise Paré in the 1500s, when he developed new techniques to treat the new sorts of wounds caused by guns.

- In the 1880s, another French surgeon, Jules-Emile Péan, further perfected this technique, including introducing the clamp (known as a hemostat) that surgeons use to hold the vessel closed while they are tying it off.

- In the 20th century, transfusion techniques were perfected so that patients could be given blood to replace what was lost during the operation. Although attempts at transfusion dated back to the 17th century, transfusions were not feasible until the discovery of blood types by Karl Landsteiner in Austria.

- In the 1910s, it was discovered that blood could be kept for longer periods by refrigerating it and adding an anticoagulant.

- The first blood banks were established in the Soviet Union in the early 1920s. Bernard Fantus at Cook County Hospital established the first blood bank in the United States in 1937.

**Infection**

- Once the surgery is complete, the patient may still die as a result of infection. For centuries, prior to the discovery of the germ theory of disease, surgeons took no precautions to prevent infection, and the mortality rate after otherwise successful procedures was often more than 50 percent.

- Surgeons seldom washed their hands before seeing patients and often wore the same frock coat while performing operations.
Indeed, a dirty coat was viewed as a sign of a surgeon’s knowledge and experience.

- The first step toward preventing infection came in 1847, when the Austrian doctor Ignaz Semmelweis noticed that medical students fresh from the dissecting room were causing more deaths in the maternity ward than midwives who assisted with births but did not frequent the dissecting room. In the face of ridicule, Semmelweis insisted that everyone thoroughly wash their hands before childbirth and other surgical procedures.

- Further development of antiseptic techniques came with Joseph Lister, whose curiosity was sparked when he read a paper by Louis Pasteur explaining how gangrene was caused by anaerobic (non-air-breathing) bacteria. Inspired by Pasteur, Lister decided to investigate how other aerobic (air-breathing) germs might be the cause of infection and to develop antiseptic techniques to kill these microorganisms.

- To kill germs, Lister started using carbolic acid, which was made from creosote and seemed promising because creosote was used to treat wood and keep it from rotting. It had also been used to treat sewage as well as fight parasites in cattle plague.

- In 1865, Lister swabbed the wound around a compound fracture in the leg of an 11-year-old boy and was pleased to find that no infection developed around the wound. Lister reported the results in the medical journals and proceeded to invent a pump that could not only spray carbolic acid on surgical instruments but also into the air of the operating room—a practice that surgeons and patients found most unpleasant.

- Finding Lister’s carbolic mist annoying, other surgeons followed the advice of the great German microbiologist Robert Koch, who recommended using steam to sterilize instruments.
• Sterilization is the basic idea behind aseptic techniques, where you avoid introducing germs into either the operating environment or wounds. Asepsis led surgeons to begin wearing sterilized white gowns, masks, and gloves and to insist on a sterile operating room that was free of unnecessary visitors.

• Surgical rubber gloves came about in 1890. At Johns Hopkins University, William Stewart Halsted was promoting aseptic techniques and using carbolic acid to sterilize both his hands and his nurse’s hands. Because his nurse had skin that was too sensitive for repeated washing with carbolic acid, Halsted asked the Goodyear Tire & Rubber Company if they could make a rubber glove that could be dipped in carbolic acid.

Suggested Reading

Ellis, *A History of Surgery*.

Magner, *A History of Medicine*.

Questions to Consider

1. Why was it that an American dentist, William Morton, pioneered anesthesia and not a surgeon?

2. What is the difference between antiseptic and aseptic techniques in surgery? Which one did Joseph Lister pioneer?

3. Why did it take until the 1930s for blood transfusions to become part of surgical practice?
Many historical eras can be described in terms of the materials that came to be used in that period because materials inform the look, feel, and scale of machines, buildings, and artifacts of an age. In this lecture, you will learn that three materials helped make the 20th century: steel, glass, and plastics. These materials transformed everyday life and people’s expectations of what the world should look like. It is important to remember that materials can constrain what inventors and technologists do in any given era, but they do not cause or define that era.

Steel

- Steel is an alloy consisting primarily of iron with other trace elements, the most important of which is carbon. In steel, the carbon content in the steel is between 0.2 and 2.1 percent by weight. Other alloying elements that are sometimes used are manganese, chromium, vanadium, and tungsten.

- Carbon and other elements act as a hardening agent, preventing the layers in the crystal lattice of the iron atom from sliding past one another. By varying the amount of alloying elements, one can control qualities in the steel such as hardness, ductility, and tensile strength.

- One application for which steel is ideal is for knife and sword blades because steel can be ground to have a sharp edge and because it is light and flexible. Since ancient times, steel has been the preferred material for swords, even though metalsmiths struggled to produce steel blades with any consistency.

- Because steel was so desirable for cutlery and tools, smiths continued to experiment with ways to make it consistently. Between 1300 and 1600, smiths in Nuremburg, Germany, found that they could make steel by heating iron bars at a red heat for days in a bed of charcoal; the resulting steel ingots could then be further annealed.
and forged to create the desired qualities. Because this process created steel with a pitted surface, the resulting product was known as blister steel.

- Although blister steel could be used to manufacture cutlery in greater quantities, an English inventor, Benjamin Huntsman, was not satisfied with the quality. Working in Sheffield in the 1740s, Huntsman devised a coke-fired furnace that was hot enough to convert Swedish iron ingots into steel.

- Known as crucible steel, Huntsman tried to convince the cutlery makers of Sheffield to buy his product, but they refused, complaining that his steel was too hard to work. In response, Huntsman sold all of his crucible steel to French knife makers, and when their improved knives began to capture the English market, the Sheffield cutlery manufacturers conceded and were forced to take up crucible steel.

- After William Kelly, Henry Bessemer, Carl Wilhelm Siemens, and Pierre-Émile Martin created new processes for making steel, the challenge then became to develop plants and a business organization that could exploit these inventions.

- In particular, the challenge was that steel cannot be cooled down and reheated later when you want to make something from it; you need to cast it or roll it right away into rails, girders, sheets, or wires. The industrialist who best addressed this challenge was Andrew Carnegie.

- To provide rails and girders, Carnegie entered the steel industry in the 1870s. Carnegie built the largest possible blast furnaces and rolling mills in the Pittsburgh region. In addition, Carnegie created a managerial structure that coordinated all of the steps involved in making steel. As a result, he could make steel cheaper than anyone else in the world, and United States became the world’s leading producer of steel by 1900.
Steel came to be used to erect larger office buildings, build a nationwide rail system, create heavily armored battleships with huge guns, and make strong critical parts in automobiles.

Glass

- Glass is an amorphous material, which means that it is between solid and liquid states. Glass is by far the most common example of an amorphous material, and the most common type of glass is soda-lime glass, composed of about 75 percent silica (SiO$_2$), sodium oxide (Na$_2$O) from soda ash, lime (CaO), and several minor additives.

- Glasses are typically brittle and optically transparent, but modern engineering has been able to create glass compositions with a remarkable array of characteristics.

- Glass was discovered in ancient Mesopotamia around the time that potters were learning to create glazes and fire pots. Taking advantage of the sand and natron they had available, ancient Egyptians created beads and beautifully colored miniature heads and figurines out of glass.

- During the Middle Ages, glass-blowing techniques evolved steadily so that glass could be used for vessels. Toward the end of the medieval era, the Venetians mastered the art of making transparent glass, which was readily used for making eyeglasses and telescope lenses.

- However, until the 19th century, glass remained a luxury material used to make items by hand for the upper class. A case in point is window glass. Other than stained glass windows, the first window glass appeared in the 17th century and was known as crown glass.

- To produce it, the glassmaker blew a large bulb, which was cut open and then spun by hand at the end of an iron rod until it flattened out into a disc. The disc was then cut into half circles and then into panes. The “crown” referred to the mark left by the iron rod. Because it required a great deal of skill and labor to produce, window glass was quite expensive.
• Through the 19th century, in order to provide the growing middle class with new products for the home—including glass bottles for preserved food and cut-glass serving dishes—inventors worked to come up with a variety of techniques and machines for producing glass products in quantity.

• One of the first improvements came in the area of window glass. In France, inventors developed a technique for introducing a large gob of molten glass onto the center of an iron-casting table. Hand rollers were used to spread the glass carefully across the table’s surface, and then the glass was allowed to cool.

• This process produced what came to be known as plate glass, but it was still quite labor intensive and expensive because both sides of the plate had to be polished by hand. Nonetheless, plate glass was used for early department store display windows.

• Further improvements followed the adoption by the glass industry of the Siemens regenerative furnace. Not only could this furnace be used to make steel, but it could also be adapted to make large quantities of glass. In the glass industry, it became known as a tank furnace. Because this furnace worked best when fired by gas, the American glass industry grew up where natural gas was discovered after the Civil War—namely, Pittsburgh, Wheeling, and Toledo.

• To take advantage of the cheap fuel, Edward Drummond Libbey moved the New England Glass Company to Toledo in 1888 and renamed it the Libbey Glass Company. Libbey was especially interested in manufacturing bottles, and he hired a talented glassmaker named Michael J. Owens, who invented the first automatic bottle-blowing machine in the 1890s.

• Together, Libbey and Owens formed the Owens Bottle Company, which merged in 1929 with the Illinois Glass Company to create the Owens-Illinois Glass Company. Today, Owens-Illinois is the largest manufacturer of glass containers in the world.
Plastics

- Technically, most plastics are polymers and are the result of the carbon atom’s unique ability to form itself into very long chains by joining together large numbers of very simple units. There are many polymers in nature, and they include natural fibers like linen and silk as well as the proteins and carbohydrates found in foods.

- In the 19th century, inventors attempted to modify natural polymers so that they could serve as substitutes for scarce materials. For instance, recognizing that there was a limited supply of ivory to use to make billiard balls, the American John Wesley Hyatt created an artificial ivory by treating cellulose with nitric acid and then blending it with camphor to create what he dubbed celluloid.

- While celluloid was used for billiard balls, it had the unfortunate tendency to explode if the balls were hit too hard, but celluloid did find other applications as the base for the new flexible film that George Eastman used in his Kodak cameras and that Edison employed in his kinetoscope.

- One drawback to celluloid was that it could not be molded, leading chemists to continue to investigate polymers. In 1872, the German chemist Adolf von Baeyer mixed phenol and formaldehyde, only to create a dark sludge that he thought was useless. However, in 1907, Leo Baekeland found that by controlling the pressure and temperature applied to phenol and formaldehyde, he could produce a hard moldable plastic that he called Bakelite.

- Bakelite was an ideal material because it could be placed in a mold and heated; once formed, it did not melt again. Bakelite found numerous applications in the electrical and electronics industry as an insulator as well as in the automobile industry for countless small parts.

- Polyethylene was developed in the 1930s by Britain’s Imperial Chemical Industries as a result of research on subjecting polymers to high temperatures and pressures. It was first used as an insulator
in submarine cables, and it proved to be highly valuable in building radar equipment during World War II because it could be used to insulate high-frequency electronic components.

- After the war, it was found that polyethylene could be shaped in a variety of ways, leading it to be used to make everything from molded plastic toys to shopping bags. Unless carefully formulated, polyethylene does not naturally degrade, prompting scientists today to develop new formulations.

- Another plastic discovered in the 1930s was nylon, developed by E. I. du Pont de Nemours & Company (DuPont Company). In 1928, DuPont hired a promising young chemist from Harvard named Wallace H. Carothers, who was excited by the controversy surrounding the nature of polymer molecules.

- While some chemists thought that polymers were held together by the same forces that operated in smaller molecules, others thought that these large molecules involved some other kind of forces. Carothers resolved this controversy by building long-chain molecules, one step at a time, employing well-understood reactions that used acids and alcohols to form esters.

- Through this research, Carothers and his team not only laid the foundation for our modern understanding of polymers, but in 1930, they also discovered two valuable materials: artificial rubber, or neoprene; and a strong manmade fiber that came to be called nylon. During the early 1940s, nylon came to be used in women’s
stockings, reinforcement cords in automobile tires, rope, and a variety of industrial applications.

**Suggested Reading**


Friedel, *Pioneer Plastic*.


Misa, *A Nation of Steel*.

**Questions to Consider**

1. What is the difference between wrought iron, cast iron, and steel? What are the advantages and disadvantages of each?

2. What did Andrew Carnegie do to make steel cheap and, hence, widely available?

3. Can you imagine a home without steel, glass, or plastic? How have these materials changed the environment in which people came to live in the 20th century?
Introduced in 1908 and priced at $850, the Model T was the first car that average Americans—farmers and workers alike—could afford. Over the next two decades, Ford produced over 15 million Model Ts. To make and sell these millions of Model Ts, Ford revolutionized production by developing the moving assembly line. This lecture focuses on the invention of the automobile. Few other inventions demonstrated the ingenuity of Americans in terms of both production and engineering, and even fewer were inventions that so thoroughly changed American life and captured the imagination of people.

The Origins of the Automobile

- In 1891, Henry Ford went to work for the local electric power company, Detroit Edison, where he rose to chief engineer. While at Detroit Edison, he caught automobile fever. He was one of hundreds of mechanically minded Americans who became fascinated with the possibility of a self-propelled vehicle.

- Since the late 1860s, several German engineers—Nikolaus Otto, Gottlieb Daimler, Wilhelm Maybach, and Karl Benz—had been working on a compact engine powered by gasoline. This engine was known as an internal combustion engine because unlike steam engines, in which the fuel was used to heat the boiler and create steam outside the engine, the fuel was introduced into the cylinder and ignited.

- The rapid expansion of the burning fuel pushed the piston and made the crankshaft turn. For early automobile engineers, then, the challenge was how to control the ignition of the fuel so that ignition did not cause the entire engine to blow up.

- They solved these problems in a variety of ways, most notably by carefully controlling the mix of air and fuel introduced into the
cylinder and by designing light but strong engine blocks (typically made out of cast iron).

- By 1886, Benz had mounted one of these engines in a carriage, but people initially showed little interest in the horseless carriage. This was, in part, because there were few roads that were smooth enough for operating such a vehicle. Equally, with the success of passenger trains and electric trolleys, people didn’t think much about the need for individual transportation.

- Demand for horseless carriages, however, changed with the rapid spread of bicycles in Europe and America in the early 1890s. Produced in quantity by using the same metalworking techniques perfected by manufacturers of clocks and firearms in New England, bicycles became a craze in Europe and America.

- Suddenly, nearly everyone had a bicycle, and it was not long before bicyclists began demanding better roads and before mechanically minded individuals—like Ford—began dreaming of individualized, self-propelled transportation.

- Inspired by detailed drawings of a horseless carriage in American Machinist, Ford built his first car in 1896. Shortly after he got this prototype on the road, he had the chance to meet Thomas Edison, and Ford described his ideas about automobiles to the great inventor. At the time, Edison was hard at work developing an electric car, but he exhorted Ford to keep working on his gas-powered buggy. Encouraged, Ford quit Detroit Edison in 1899 in order to manufacture automobiles.

- As with many new technological ventures, it took Ford several tries to establish the right sort of company. Ford first set up the Detroit Automobile Company, which made 25 cars and then failed. Undaunted, Ford found a new set of backers and launched the Henry Ford Motor Company in 1901.
Anxious to get manufacturing on a sound footing, Ford’s backers in this second company brought in a master machinist named Henry Leland. Trained in the New England firearms industry, Leland knew how to make products with interchangeable parts.

Up to this point, automobile makers in Detroit had emulated carriage manufacturers and built each car individually; the parts were purchased from different suppliers and then assembled into a car by a team of craftsmen.

Leland told the automakers that to make any money, they were going to have to assemble cars using interchangeable parts. Although Ford grasped this idea of interchangeability, Ford and Leland soon clashed, and Ford fired Leland. Ford clashed not only with Leland, but with his backers as well. While they wanted to build expensive cars for the luxury market, Ford wanted to produce low-priced ones for a broad market.

Disgusted with his backers, Ford started a third firm, the Ford Motor Company, in 1903, with investors putting up $28,000 cash. Between 1904 and 1905, this company sold 1,745 cars and paid $288,000 in dividends.

Concluding that backers would always interfere with his plans, Ford used his dividends to buy out the other investors. Now independent, Ford began manufacturing low-priced automobiles, and he brought out his Model N, priced at $600. Ford sold 9,000 cars and took in $5.8 million between 1906 and 1907.

The Model T and the Moving Assembly Line

Building on the success of the Model N, Ford started planning a new car in a locked room in the back of his plant. Dubbed the Model T, Ford’s new design was to be a low-priced automobile for a mass audience.

Recognizing that more than half of all Americans still lived in the country in 1907, Ford decided that the Model T would have to be
rugged and easy to repair if it was going to be useful to farmers. To give the car strength but keep it light, Ford made key parts out of vanadium steel, which was three times stronger than ordinary steel.

- Ford realized that to make cheap cars, he would have to make a lot of them, and this led him to experiment extensively with production methods. Borrowing existing practices from other metalworking industries, Ford and his team created a line production system, in which they placed machines and workers in a carefully planned sequence of operations.

- Next, his engineers began installing conveyor belts to carry parts to the workers; this practice was similar to the conveyor belts used to assemble orders at the Sears central warehouse. Ford and his team then began using conveyor belts to create a moving assembly line, where workers stood along the moving belt and performed their task on parts moving past them.

- Ford tried the moving line first for assembling the flywheel magneto and then the engine; in 1914, they created the assembly line along which the chassis and the car were completed.

- Ford’s assembly line principles allowed output to soar, but this increase came at the price of eliminating skill and worker satisfaction. His company was experiencing extremely high worker turnover, on the order of 300 percent annually. Workers would come to work on the line, become disgusted with the monotony, and quit.

- In response, Ford announced in 1914 that he would increase the starting wage at his plant to five dollars for an eight-hour day—doubling the prevailing wages in the automobile industry. These higher wages gave Ford an advantage in recruiting the best workers and demanding higher levels of effort from them; it also allowed Ford to increase the speed of the line.

- As Model Ts became cheaper, farmers were able to carry their produce to market and come to town more often, city dwellers
chose to move away from work downtown and relocate to single-family homes in suburbs, young people used the car to establish their independence from their parents, and individuals generally came to expect that they could travel wherever and whenever they wanted.

- While the moving assembly line allowed him to increase output dramatically, Ford was determined to continue to drive down his costs, lower the price of the Model T, and capture more of the automobile market.

- In his relentless pursuit of efficiency, Ford broke ground for a huge plant at River Rouge in Dearborn, Michigan, in 1916. When completed in 1927, “the Rouge” consisted of dozens of mills, forges, docks, and assembly lines. The Rouge produced its own steel, glass, paper, and fabric—all of which were converted

The Model T was manufactured by the Ford Motor Company from 1908 to 1927.
into automobile components on subassembly lines. In turn, these components were assembled into automobiles on the main line.

- To supply the Rouge, Ford integrated backward and purchased forests, coal mines, iron-ore deposits, and even rubber plantations in South America. To carry materials to the Rouge, Ford invested in a railroad and a fleet of Great Lakes steamers.

The Limits of Mass Production

- Ford’s efforts to cut manufacturing costs paid off, and he was able to reduce the price of the Model T from $850 in 1907 to $263 in 1927. By 1927, Ford had sold 15 million Model Ts, and they constituted half of the automobiles manufactured up to that time in the United States.

- Starting with capital of $28,000, the Ford Motor Company was now worth $715 million. Ford personally controlled the company, and he was now a billionaire. But Ford did not fully comprehend the changing nature of the automobile market. To avoid the costs of having to retool his plants, Ford had “frozen” the design of the Model T.

- Between 1907 and 1927, the Model T remained the same—an open car that was started by turning a crank and that had a temperamental “planetary” transmission and a maximum speed of 40–45 miles per hour. Because black enamel dried faster than other colors, Ford insisted that the Model T be painted black.

- Between 1907 and 1927, other automakers had introduced faster cars with electric starters and closed bodies. Customers could also choose the color they wanted. Many Americans bought a Model T as their first car, but then as their income grew, they often chose to replace their “Tin Lizzies” with a new car with better features.

- At Ford’s major rival, General Motors, Alfred P. Sloan and his managers studied how Americans were purchasing automobiles,
and in the mid-1920s, GM began offering new models with new features every year. GM also offered a whole range of cars.

- As Model T sales slumped in the mid-1920s, Ford took a drastic step. While he and his engineers designed a new car, the Model A, he shut down the River Rouge plant and produced no cars in 1927. During that year, GM and the other automakers had the entire automobile market to themselves, and they gained a great deal of ground.

- While Americans liked the Model A and bought 1.4 million of them in 1929, Ford never recaptured a dominant share of the market, and GM became the leading American car manufacturer. Unlike Ford, who had concentrated on production, Sloan at GM realized that long-term success would depend on matching production with marketing.

**Suggested Reading**

Flink, *The Car Culture*.

Watts, *The People’s Tycoon*.

White, “Farewell, My Lovely.”

**Questions to Consider**

1. Why did Henry Ford institute the five-dollar day?

2. Ford is famous for saying: “You could have a Model T in any color as long as it was black.” Why did Ford paint his cars black? How did limiting the color of Model Ts contribute to its ultimate demise in the 1920s?

3. What business practices did Alfred P. Sloan at General Motors borrow from Ford? What did he do differently?
Aviation—The “Wright” Time for Flight
Lecture 26

Aviation is an example of a technology that has been strongly influenced by military needs, and its civilian applications (such as passenger travel) are spillover effects of military investment. As you will learn in this lecture, aviation developed in the 20th century not only because the right people—the Wright Brothers—took it up, but also because the circumstances—in a political and military sense—were right. Today, we take aviation for granted. Perhaps we need to occasionally look up at an airplane and marvel at the human creativity and the social context that made flight possible.

Early Flight

- There are two kinds of aircraft: lighter-than-air craft, such as balloons, dirigibles, and blimps; and heavier-than-air craft, such as airplanes and helicopters. The Montgolfier brothers flew the first lighter-than-air craft—a hot-air balloon—in 1783.

- For centuries, people thought that the most likely way to fly (in heavier-than-air craft) would be to imitate the flapping wings of a bird. A good example is Leonardo’s ornithopter, a device he sketched in one of his many notebooks.

- However, by the 19th century, the English aristocrat Sir George Cayley had come to realize that the way forward was to worry less about flapping wings than understanding their shape. After experimenting with flapping wings, Cayley decided that the shape of the wing could create lift as long as the wing was moving through the air.

- With the right shape, a larger portion of the air goes underneath the wing, creating a pressure differential that creates lift. The pressure is greater underneath the wing than above it, thus exerting an upward force. For decades, Cayley studied the shape of wings
and the amount of lift that each shape produced, and in 1853, he sent one of his servants soaring for 500 meters across a valley in Yorkshire, England.

- During the closing decades of the 19th century, several inventors—such as Otto Lilienthal and Octave Chanute—followed up on Cayley’s investigations and developed their own winged gliders. Chanute also published a series of tables showing how differently shaped wings provided various amounts of lift.

- Of these early experimenters, Samuel Pierpont Langley, an astronomer and Secretary of the Smithsonian Institution, came the closest to achieving manned flight before the Wright brothers. Assuming that the amount of power was crucial for flight, Langley concentrated on developing lighter and more powerful engines.

- In 1896, Langley successfully flew an unmanned steam-powered craft over the Potomac River near Washington DC. Langley set out to build a manned aircraft with an internal combustion engine that was ready for flight in 1903, but his aircraft was damaged as it was launched by catapult and crashed into the Potomac. Disheartened, Langley abandoned his efforts.

The Wright Brothers

- At about the same time, bicycle mechanics Wilbur and Orville Wright followed up on Cayley’s work with their own gliders and careful experiments in a homemade wind tunnel. In the 1890s, as they began to investigate flight, the Wrights made a critical decision that the challenge was not power (as Langley had assumed) but, rather, control.

- In approaching control, the Wrights made a further critical decision: An airplane would be more like a bicycle than a ship, requiring forward motion and continuous control for stability.

- The Wrights decided to control their airplane by wing warping. Reasoning from how a cardboard box can be twisted, the Wrights
realized that they could control the lift under the wings so that they could turn the plane and move it up/down. Today, the same control is achieved by flaps on the back edge of wings.

- To test out their ideas, the Wrights traveled each fall to Kitty Hawk on the Outer Banks of North Carolina. They chose Kitty Hawk because they were told by the U.S. Weather Service that Kitty Hawk had the strongest average winds. At Kitty Hawk, they flew a number of gliders to test out their ideas about control.

- At the same time, though, the Wrights realized that there was something wrong with Cayley’s lift tables; they were not getting the same amount of lift with their wings that his tables predicted. In response, the Wright brothers built their own wind tunnel in their bicycle shop in Dayton, Ohio. There, they tested a range of wing shapes and found which ones gave optimal lift.

- In the fall of 1903, the Wrights combined all of these decisions—about the engine, wing warping and wing shape—to create their first flyer. On 17 December 1903, 10 days after Langley’s failure on the Potomac, the Wrights flew successfully at Kitty Hawk. It was only 852 feet for 59 seconds, but it was enough to convince them that they had invented the first airplane.

- Although they first flew in 1903, the Wrights really only demonstrated the full capability of their invention in 1905 when outside Dayton, Wilbur flew more than 24 miles in 38 minutes—banking and turning, climbing and descending at will. Moreover, the Wrights were not recognized as the pioneers of flight until they demonstrated their airplane in France in 1908.

The Military and Aviation
- Having built a functional airplane, the Wrights proceeded to patent their invention. Now, the challenge became finding a customer for their invention. In the 1900s, the most promising customers proved to be the military in both the United States and Europe because both powers were in a naval arms race, and nations were rushing
to build their own battleships and looking at inventions that might help protect them from attack.

- Consequently, the Wrights sold their first plane to Signal Corps of the U.S. Army in 1909. During the next few years, the other European powers acquired airplanes and began experimenting with how they might be used in war.

- During World War I, both the British and Germans relied on airplanes for aerial reconnaissance—for early information on troop movements during trench warfare—and the information gathered was of such importance that both sides launched fighter aircraft to defend the reconnaissance missions, leading to the beginning of aerial dogfights.

- In the 1920s and 1930s, aviation grew largely as a result of government support. European governments created airlines, with KLM (the Dutch airline) being the first in 1919, and the U.S. Post Office sponsored airmail service, which encouraged the development of American airlines.

The most famous airplane at the beginning of World War II was the B-17 Flying Fortress, which could cruise for 2,000 miles.
At the same time, there was a great deal of research undertaken to understand the underlying dynamics of flight. In the United States, a portion of this research was funded by the federal government through the forerunner of NASA, the National Advisory Committee for Aeronautics (NACA), and the work was performed at universities.

Between the World Wars, the Americans, Germans, and British realized that airplanes would be essential in future wars, and they pushed engineers to develop planes that could carry large payloads of bombs faster and over longer distances.

Military bombers were the weapon of choice in World War II, and both sides raced to create bombers that could destroy both cities and industrial sites such as factories, hydroelectric dams, and railroads.

In this context, American airplane manufacturers developed progressively larger bombers, and they applied the mass-production techniques developed in the automobile industry to produce thousands of planes.

While the effectiveness of strategic bombing in World War II is still debated by military analysts, the United States decided after the war that it would rely on long-range bombers (such as the B-52) to deliver nuclear bombs.

In the 1950s, aircraft firms like Boeing continued to design and build planes for the U.S. military, but they were anxious to keep their large plants operating at capacity by leveraging the engineering expertise they had acquired on military projects and using it to create civilian aircraft.

In the 1950s, Boeing created its first and famous jet airliner, the 707. Although not the first jet airliner, the 707 was the first commercially successful jet passenger plane, and it ushered in the jet age.
Jet Engines

- Early aviation pioneers recognized that they needed a powerful but lightweight engine, and they debated the merits of several different power sources—while Langley used steam power, the Wrights focused on a piston-driven gasoline engine.

- Beginning in the late 1920s, Frank Whittle in England and Hans von Ohain in Germany began investigating turbojet engines. Just as turbines had come to replace piston engines in using steam to generate electricity, Whittle and von Ohain wondered if it might be possible to use a turbine engine to power a plane. Their basic idea was to use a combination of a compression and combustion to speed up airflow and create thrust.

- Hence, a typical turbojet consists of an air inlet, an air compressor, a combustion chamber, a gas turbine (that drives the air compressor), and a nozzle. A turbojet works because incoming air is compressed into the chamber; heated and expanded by the fuel combustion; and then allowed to expand out through the turbine into the nozzle, where it is accelerated to high speed to provide propulsion.

- The first turbojet aircraft to fly was a prototype—the Heinkel HE 178, tested by the German Air Force, or Luftwaffe, in 1939. While the jet engine was ideal for creating fast fighter planes, Hitler insisted on trying to develop a jet-powered bomber, so the only jet fighter to see service before the end of World War II was the Messerschmitt Me 262.

- After the war, the United States, Britain, and the Soviets all sought to build their own jet-powered bombers and passenger planes. They did so not just because jets could attain higher speeds, but also because jet aircraft were more economical to fly at higher altitudes.

- Pound for pound, jet engines could deliver far more thrust than existing piston engines, and they involved far fewer moving parts. However, at lower altitudes, turboprop engines are more fuel
efficient and are more maneuverable, which is why they are used on short-hop, or commuter, flights.

- In the 1960s, turbojets were replaced by turbofan engines. When operated at subsonic speeds, conventional turbojet engines generate an exhaust that ends up traveling very fast backward and wastes energy. Consequently, turbofans are used for airliners because they give an exhaust speed that is better suited for subsonic airliners. By emitting the exhaust so that it ends up traveling more slowly, better fuel consumption is achieved as well as higher thrust at low speeds. In addition, the lower exhaust speed gives much lower noise.

**Suggested Reading**

Constant, *The Origins of the Turbojet Revolution*.

Crouch, *The Bishop’s Boys*.

Smith, “The Development of Aviation.”

**Questions to Consider**

1. What were the political and military conditions that favored the invention and development of the airplane in the early 20th century?

2. How is an airplane more like a bicycle than a ship on the ocean?

3. What are some of the reasons jet engines replaced piston engines on airplanes after World War II?
Perhaps one of the most remarkable stories of inventors and companies puzzling over how to develop a new communications technology is the story of radio and television broadcasting—broadcasting was not something that anyone knowledgeable about radio anticipated. This integration of technology, distribution, and content was a complex process and frequently involved the clash of lively personalities. In this lecture, you will learn about Tesla versus Marconi, de Forest versus Armstrong, and Sarnoff versus Farnsworth.

**Marconi and His Rivals**

- Like other developments in electricity, radio began with discoveries in Europe. In Britain, while developing a theoretical understanding of Faraday’s ideas about electromagnetic induction, James Clerk Maxwell suggested that there must exist a range of electromagnetic waves, of which visible light was only one form.

- Seeking evidence of these invisible waves, Heinrich Hertz in Germany showed in 1887 that these waves could be generated by an electric spark and could be detected 20 meters (66 feet) from the source.

- One of the first people to pounce on Hertz’s discovery and try to develop it into a new technology was Nikola Tesla, the inventor of the alternating current motor. After learning about Hertz’s experiments, Tesla not only duplicated Hertz’s work but created an even more powerful device: a high-frequency, high-voltage transformer that we now call a Tesla coil. Using this new coil, Tesla found that he could create a powerful electric field that would illuminate lamps or power motors without using any wires.

- Tesla also learned how radio signals could be tuned to a particular frequency, which he demonstrated by using differently tuned signals
to operate a remote-controlled boat in 1898. However, concerned that radio waves would just fly off into space and that only a tiny fraction of the energy produced by his transmitter would ever reach a receiver, Tesla decided to concentrate on sending oscillating currents through the Earth’s crust rather than beaming radio waves.

- Tesla was able to detect power up to 30 miles away; while his coil was running, he took a detector on board a Hudson River steamer, and he received signals all the way up the river to West Point. Such results convinced Tesla that he should build a large-scale system, which he did first in Colorado in 1899 and then at Wardencliff on Long Island from 1901 to 1905.

- However, before Tesla got any positive results, he ran out of money and was overtaken by a young Italian inventor named Guglielmo Marconi. In the early 1890s, Marconi decided that Hertz’s waves could be used to create a system for sending telegraph messages (in Morse code dots and dashes) without wires.

- Unlike Tesla, who concentrated on using radio waves to transmit power, Marconi believed that the future of radio was in communications. In particular, Marconi focused on the lucrative ship-to-shore communications business, where he was not competing with anyone.

- Marconi found that when his transmitter and receiver were grounded (connected to the earth) and when he increased the height of his antenna, he could greatly extend the signal’s range. In 1901, Marconi succeeded in transmitting the Morse code letter s across the Atlantic from England to Newfoundland. Soon afterward, ships used Marconi’s equipment to communicate with each other and with the shore over distances up to 2,000 miles (3,200 kilometers).

- Along with Tesla, another early rival of Marconi was the Canadian-born inventor Reginald Fessenden, who experimented with sending voice messages. In 1901, he invented the heterodyne receiver, which converted high-frequency waves into low-frequency waves.
that could be heard in headphones. In 1902, building on the work of Tesla and Ernst Alexanderson of GE, Fessenden designed his own high-speed alternating current generator (or alternator), which could produce powerful high-frequency radio waves.

- As late as 1912, while Marconi had made many improvements in his equipment, he was still using a crude receiver to detect incoming signals. To replace it, several inventors—John Ambrose Fleming with British Marconi and an American named Lee de Forest—experimented with modified incandescent lamps.

- Following up on Fleming’s work, de Forest added to his bulb a small wire grid that could carry its own current and found that his bulb could operate not only as a wave detector but also as an amplifier. De Forest called his bulb the Audion, and it was the ancestor to all the vacuum tubes on which radio broadcasting would be based in the 1920s.

- Several companies and inventors lost no time in applying de Forest’s Audion to their needs. AT&T promptly licensed de Forest’s Audion and used it in the first coast-to-coast long-distance telephone call in 1914.

- Meanwhile, an engineering student at Columbia University, Edwin H. Armstrong, discovered that if the current coming off the plate of an Audion was fed back to its grid—creating what was called a regenerative circuit—signals were further amplified, making it possible to use a loudspeaker instead of headphones.

- A few months later, Armstrong figured out how a regenerative circuit could be used to generate radio waves, thus doing away with the cumbersome alternators that Marconi, Fessenden, and others were using.

**The Rise of Broadcasting**

- When World War I broke out in 1914, it was immediately clear that radio would play an important role in coordinating troop
movements on land and providing communications between warships at sea. In 1919, the U.S. Navy arranged with the major companies in the radio industry—American Marconi, AT&T, and General Electric—to create a new company, the Radio Corporation of America (RCA).

- Seeing that radio broadcasting was popular and likely to grow, RCA hastily agreed in 1921 to bring Westinghouse into the consortium. The first Westinghouse stations were followed by dozens of others, started by department stores, newspapers, universities, and entrepreneurs. By 1922, there were 600 stations in operation. With so many stations to tune in to, individual Americans began buying radios.

- As broadcasting stations proliferated, the managers at the major companies began to wonder how to pay for the programs being broadcast. In 1922, AT&T discovered a solution: Just as it had charged users to talk over its telephone lines, AT&T began to charge companies for airtime, in effect creating the first radio commercials.

- Given how fast the radio industry was changing, AT&T managers started to consider exiting the RCA consortium and striking out on their own. To placate AT&T, RCA’s president, David Sarnoff, proposed in 1926 that AT&T, GE, and Westinghouse create another new company. Following the AT&T model, this new company would make money by selling airtime to advertisers.

- This new company was the National Broadcasting Company (NBC), the first media network. NBC was soon followed by a second network, the Columbia Broadcasting System (CBS), created by several entrepreneurs and then purchased by William S. Paley.

**The Invention of Television**

- No sooner had Bell invented the telephone than people began imagining that, along with voices, pictures might be sent by wire from place to place. While many people ridiculed the idea of “seeing at a distance,” inventors were soon at work trying to make it a reality.
• In 1880, a French engineer named Maurice LeBlanc suggested that as a first step, a scene would have to be broken down into a series of elements that could be transmitted sequentially over a telegraph wire. LeBlanc suggested scanning the image from left to right, row by row, but he was unable to come up with a device to “dissect” the image.

• Instead, a German engineer named Paul Nipkow invented an ingenious scanning disk. In 1884, Nipkow patented an Elektrisches Telescop, which consisted of a rotating disk with an inward-spiraling sequence of holes. As the disk rotated, the outermost hole would move across the scene, letting through light from the first “line” of the picture. The next hole would do the same, only slightly lower, and so on with the holes in the disk. One complete revolution of the disk would provide a complete picture or scan of the scene.

• Just as Nipkow showed a mechanical way of scanning images, A. A. Campbell Swinton, an electrical engineer in Scotland, suggested an electronic way of scanning. In 1908, Swinton proposed the basic idea for a television picture tube. Like other early investigators of television, Swinton sketched his idea but left it to others to build the first picture tube.

• Two inventors—Philo T. Farnsworth and Vladimir Zworykin—raced to be the first to perfect an electronic television camera.
Farnsworth began by rediscovering LeBlanc’s idea of scanning and planning how to scan images electronically.

- In 1927, Farnsworth set up a small laboratory in San Francisco, where he hoped to develop electronic television. By 1928, Farnsworth had perfected his television camera, or “image dissector,” so that he could hold a demonstration for the press.

- In the meantime, Vladimir Zworykin was also working on his own version of electronic television. During the early 1920s, he conducted experiments on his own system based on cathode-ray tubes, and in 1930, he was recruited by Sarnoff to work at RCA.

- Sarnoff sent Zworykin to San Francisco to talk with Farnsworth and find out what he had accomplished. Shortly thereafter, Sarnoff offered Farnsworth $100,000 for his television patents, but Farnsworth turned Sarnoff down, preferring to go to work for Philco in Philadelphia.

- Because they could not work with Farnsworth, Zworykin and RCA brought out their own Iconoscope camera tube in 1931. RCA then sued Farnsworth for infringement, leading to several years of litigation.

- In 1939, anxious to demonstrate television at the upcoming New York World’s Fair, RCA reluctantly agreed to settle and pay patent royalties to Farnsworth. As a result, RCA was able to broadcast President Roosevelt speaking at the opening ceremonies of the fair.

- Although further development of television was delayed by World War II, television took off in the years immediately after the war. In terms of programming, television was quickly dominated by the three existing radio networks: NBC, CBS, and ABC.

- While much of the programming of early television duplicated radio—news, sports, soap operas, comedy, and Westerns—the
new medium also stimulated the creation of new programs such as television plays and game shows.

- Because television was highly dependent on advertising revenue from the manufacturers of national brands, the networks sought shows that they thought would reach the largest possible audiences of white middle-class consumers. Consequently, critics soon complained that the networks catered to a bland, middle-of-the-road audience.

**Suggested Reading**


Lewis, *Empire of the Air*.

Lubar, *InfoCulture*.

Schwartz, *The Last Lone Inventor*.

**Questions to Consider**

1. How did the clash of personalities shape the evolution of radio and television? Did you find this surprising for two 20th-century inventions, because we tend to assume that recent inventions are largely the product of impersonal corporations?

2. How were mechanical and electronic televisions similar? How were they different? Could mechanical televisions be made to work?

3. Why was it that, even from the 1950s, people complained that television programs were bland and predictable?
Once heralded as a utopian technology that could produce electricity “so cheap that it would not need to be metered,” nuclear technology has presented significant military and environmental risks. In this lecture, you will learn about nuclear fission and nuclear fusion in the context of war, innovation, and disaster. Specifically, you will learn about World War II and the Cold War, the invention of the pressurized water reactor, and the accident at Three Mile Island and the disaster at Fukushima Daiichi.

The Discovery of Atomic Fission

- The nuclear age began in 1938 when three German scientists—Otto Hahn, Lise Meitner, and Fritz Strassmann—successfully split a uranium atom by bombarding a uranium isotope with neutrons. As they did so, they found that collisions between neutrons and the uranium atoms caused the atoms to split, releasing energy and more neutrons. As the fission process went on, the uranium atoms decomposed into various radioactive elements.

- Physicists in Germany, Britain, and the United States quickly realized that the discovery of nuclear fission might mean that one could make a bomb of unprecedented power. The question was whether one could figure out how to get a uranium sample to reach critical mass, the point at which the nuclear reactions going on inside the sample can make up for the neutrons leaving the sample.

- In the United States, two émigré physicists—Leo Szilard from Hungary and Enrico Fermi from Italy—conducted their own fission experiments, which confirmed that as more neutrons were released, the process became a chain reaction capable of sustaining itself and producing great amounts of energy.

- Meanwhile, the British government was pursuing its own atomic bomb research (under the code name MAUD), and in the spring of
1941, it warned the Americans that a bomb was practical and could be built in two years, possibly by Germany. The British warning led President Roosevelt to order the Department of War to begin a top-secret project to develop an atomic bomb.

- Code named the Manhattan Project, the development of the atomic bomb was led by Brigadier General Leslie R. Groves. As project leader, Groves faced numerous challenges, but most of all, he had to balance the need for further scientific research with the necessity of building an actual bomb as quickly as possible.

- In this balancing act, Groves worked with both a team of talented physicists (including Fermi, Szilard, and J. Robert Oppenheimer) as well as engineers from the DuPont Company.

- Initially, Groves and the physicists planned to build a bomb using uranium, but in February 1941, Glenn Seaborg and others at the University of California, Berkeley, isolated a new manmade element that they called plutonium. Seaborg reported that slow neutrons caused plutonium to split even more easily than uranium.

- To build the actual bomb, Groves appointed J. Robert Oppenheimer to direct operations at Los Alamos, New Mexico. Oppenheimer’s team designed a firing mechanism that pushed the proper amount of plutonium together, setting off a rapid chain reaction and releasing enormous amounts of energy.

- Oppenheimer’s team tested their bomb at Alamogordo, New Mexico, on July 16, 1945. The energy released by the bomb was equivalent to the detonation of 20,000 tons of TNT.

**Hiroshima and Nagasaki**
- As Allied forces gained control of Germany in early 1945, it became clear that Japan would be the target for the bomb. Allied military commanders estimated that to invade and defeat Japan would require a huge army, and tens of thousands of Allied soldiers might be killed.
Hence, after Roosevelt died in April 1945, the new President, Harry Truman, authorized the military to use the bomb on Japan. On August 6, 1945, a B-29 bomber, the Enola Gay, dropped the first atomic bomb called “Little Boy” on the Japanese city of Hiroshima.

A second bomb, “Fat Man,” was dropped three days later on the city of Nagasaki. According to official estimates, 70,000 people were killed immediately by the Hiroshima bomb, and another 200,000 died over the next five years from wounds and radiation poisoning. At Nagasaki, about 40,000 were killed by the blast and another 140,000 in subsequent years.

Following these two horrific bombings, Japan surrendered unconditionally on August 14, 1945. These are the only times that nuclear weapons have been used in war.

The Coming of the Cold War

Historians have long debated whether the atomic bomb was used by Truman not only to defeat the Japanese, but also as a warning to Soviet Russia. During the last months of the war, the Soviet army invaded not only Germany, but also other Eastern European countries, including Bulgaria, Poland, Austria, Hungary, and Czechoslovakia.

Truman feared that the Soviets would not withdraw from these countries and that the Soviets might indeed try to create Communist regimes in Europe and elsewhere. Hence, Truman hoped that the atomic bomb might discourage the Soviets from further aggression.

As a result, Truman shared the secrets of the atomic bomb with Britain and, later, France but deliberately withheld information from the Soviets. In response, the Soviets developed their own atomic bomb that they exploded in 1949.

Horrified that the Soviets were able to catch up so quickly, Truman authorized in 1950 the development of an even more powerful weapon: the hydrogen bomb. Unlike the first atomic bombs that
relied on splitting atoms, or fission, the hydrogen bomb works on nuclear fusion.

- In nuclear fusion, the nuclei of atoms join together, or fuse, to form a heavier nucleus. This happens only under very hot conditions. The explosion of an atomic bomb inside a hydrogen bomb provides the heat to start fusion. Fusion releases energy due to the overall loss in mass.

- The hydrogen bomb is thousands of times more powerful than an atomic bomb. A common hydrogen bomb has the power of up to 10 megatons. In 1952, the United States exploded the first hydrogen bomb, and the Soviets followed with their own in 1954.

- Because neither the Americans nor the Soviets could gain the ultimate technological advantage, an arms race began in the 1950s with both sides trying to amass the largest number of warheads. The Cold War had begun.

Hydrogen bombs were tested at a site in Nevada in the 1950s.
The Pressurized Water Reactor

- In 1946, the U.S. Navy assigned a team headed by Captain Hyman Rickover to work with the Atomic Energy Commission (AEC) to investigate how atomic power might be used to power ships and submarines. Although there were several alternatives for designing a nuclear reactor, Rickover chose to develop a pressurized water reactor for use in submarines.

- In a pressurized water reactor, the primary coolant, water, is pumped under high pressure to the reactor core, where it is heated by the energy generated by uranium fission. The heated water then flows to a steam generator, where it transfers its thermal energy to a secondary system where steam is generated. This steam then drives the turbines that in turn spin the electric generators. In a nuclear sub, the electricity from the generators drives several motors that power the propellers.

- Rickover’s pressurized water reactor was first installed in SSN-571, the *Nautilus*, which was launched in 1954. Rickover went on to supervise the installation of nuclear reactors in dozens of other subs and aircraft carriers. To ensure that crews could operate these ships safely, he instituted special training programs and insisted on interviewing each and every candidate for the nuclear officer corps.

- During the 1950s, both the British and the French also developed civilian atomic power, and the British were the first to deliver electricity from an atomic power plant at Calder Hall in 1956.

- To keep up with European developments, the AEC asked Rickover to work with Westinghouse to install a pressurized water reactor in a demonstration plant at Shippingport, Pennsylvania, which began generating electricity in 1957. While it was never economically efficient, its performance convinced a number of American utility companies to build their own nuclear power plants.
Three Mile Island and Fukushima Daiichi

- The American nuclear power industry grew steadily until an accident in 1979 at a plant at Three Mile Island in central Pennsylvania. Three Mile Island was built by General Public Utilities Corporation. It consists of two pressurized water reactors—one built in 1974 and the second in 1978. Together, the two reactors could generate 1,700 megawatts of power.

- The accident in the second unit began with a simple plumbing breakdown. A small valve opened to relieve pressure in the reactor, but it malfunctioned and failed to close. This caused cooling water to drain and the core to overheat.

- The machines monitoring conditions inside the nuclear core provided false information, so plant operators shut down the very emergency water that would have cooled the nuclear core and solved the problem. The core reached 4,300 degrees Fahrenheit.

- Fortunately, the nuclear plant’s designers were able to reach the plant operators several hours later and instructed them to turn the water back on so that conditions stabilized. Nonetheless, the accident caused a release of radioactivity into the atmosphere, but fortunately, there were no deaths.

- A subsequent review of the accident concluded that it had been caused by poor training of the operators. In the 30 years since Three Mile Island, not a single nuclear power plant has been approved for development.

- Further concerns about the safety of nuclear power were raised by the accident at Chernobyl in 1986 and most recently by the 2011 disaster at Fukushima in Japan. The Fukushima plant comprised six separate boiling water reactors originally designed by General Electric and operated by the Tokyo Electric and Power Company (TEPCO).
On 11 March, Japan experienced a severe earthquake and tsunami. Immediately after the earthquake, the reactors that generate electricity shut down automatically, and emergency generators came online to power the coolant systems.

However, the tsunami following the earthquake quickly flooded the low-lying rooms in which the emergency generators were housed. The flooded generators failed, cutting power to the critical pumps that must circulate coolant water needed to keep the reactors from melting down.

As the pumps stopped, the reactors overheated over the next few days due to the normal high-radioactive-decay heat produced. At this point, only prompt flooding of the reactors with seawater could have cooled the reactors quickly enough to prevent meltdown.

However, because the seawater would permanently ruin the reactors, TEPCO and the government hesitated to flood the complex. Flooding with seawater was finally commenced only after the government ordered that seawater be used, but it was too late to prevent meltdown. As the seawater boiled away, levels in the fuel rod pools dropped, and they melted down.

Suggested Reading

Hewlett, “Man Harnesses the Atom.”
Hewlett, Nuclear Navy.
Hughes, American Genesis.
Rhodes, The Making of the Atomic Bomb.

Questions to Consider

1. Although most histories of the atomic bomb focus on the role of the scientists, what role did engineers from the DuPont Company play in developing the first bomb?
2. What is the difference between an atomic bomb and a hydrogen bomb?

3. Most civilian nuclear power plants are based on the reactor technology promoted by Admiral Hyman Rickover of the U.S. Navy. Why is that Rickover was able to prevent catastrophic accidents from occurring on board ships, but the civilian nuclear industry has had accidents like Three Mile Island and Fukushima?
In this lecture, you will learn how the central artifacts of consumer society—household appliances—were invented. You will learn how appliances are the confluence of several themes that have been discussed in previous lectures. They came about as a result of the widespread availability of electric power in the early 20th century and the capacity of American companies to mass-produce complex products—not only the Model T, but also many other goods. Moreover, appliances were distributed to consumers via department stores and other retail outlets.

The First Household Appliances

- In the 19th century, many American families purchased a range of new consumer products, including radios, phonographs, washing machines, refrigerators, gas and electric stoves, and vacuum cleaners. These new products allowed Americans to enjoy a new level of personal comfort, and middle-class Americans came to see these products as proof of the quality of the American way of life.

- While we tend to rationalize appliances because they seem to require less work, some historians and sociologists would argue that their real function is to serve as social and cultural markers, signaling who belongs to middle class in America and confirming the virtue of the capitalist system.

- Though we tend to see them symbolically, stripped to their essentials, household appliances are electromechanical devices that are used to perform domestic chores. They began to turn up in European and American households in the 19th century, when as a result of the industrial revolution, it seemed more acceptable to have machines come inside the home—traditionally viewed as a female space. Prior to this, machines were regarded as appropriate only for nondomestic activities and were to be controlled and used mostly by men.
One of the first appliances to visit the home was the vacuum cleaner. As middle-class families installed carpets in their homes through the middle decades of the 19th century, there came the need to clean these carpets periodically. In some cases, the carpets were rolled up and taken outside, where they could be hung up and beaten by servants or children.

While some enterprising inventors introduced mechanical sweepers in the 1860s as well as machines for blowing the dust out of carpets, most historians regard Hubert Cecil Booth of England as the inventor of the motorized vacuum cleaner, in 1901.

After seeing a demonstration of an American machine that blew the dust out of carpets and off furniture, Booth could not help but think that it would be better to reverse the process and suck up the dust. To test this idea, Booth laid a handkerchief on the seat of a restaurant chair, put his mouth to the handkerchief, and then tried to suck up as much dust as he could onto the handkerchief. Upon seeing the dust and dirt collected on the underside of the handkerchief, he realized that the idea could work.

Booth designed a large machine, powered first by an internal combustion engine and later by an electric motor that was mounted on the back of a horse-drawn wagon. Nicknamed the “Puffing Billy,” Booth’s horse-drawn vacuum cleaner relied upon air drawn by a piston pump through a cloth filter. It did not contain any brushes; all of the cleaning was done by suction through long tubes with nozzles on the ends.

Rather than sell this big machine, Booth instead sold cleaning services by sending his wagons throughout towns and cities in England. The vans of the British Vacuum Cleaning Company were bright red; uniformed operators would haul a hose off the van and route it through the windows of a building to reach all of the rooms inside.
• Although people complained about the noise of his machine (it frightened the horses), Booth’s invention gained widespread approval when he used it to clean the carpets of Westminster Abbey prior to the coronation of Edward VII in 1902. Similar companies were set up in American cities.

• But for vacuum cleaners to actually become used in the house by housewives, it was necessary to scale the equipment down and power it by electricity. This became possible as electric power and electric motors become more widely available in the late 19th and early 20th centuries.

• The first portable vacuum cleaner was invented in 1907 by James Murray Spangler, a janitor from Canton, Ohio. In addition to suction that used an electric fan, a box, and one of his wife’s pillowcases, Spangler’s design incorporated a rotating brush to loosen debris in the carpet.

• Because he could not afford to build a prototype, Spangler sold his patent to his cousin’s husband, William Henry Hoover, in 1908. Hoover manufactured leather horse harnesses, but he recognized that the automobile was making his product obsolete, so Hoover was looking for a new market to move into.

• Hoover had Spangler’s machine redesigned with a steel casing, casters, and attachments. Hoover sold his first vacuum in 1908, the Model O, for $60. Subsequent innovations included the first disposable filter bags in the 1920s and the first upright vacuum cleaner in 1926.

The Washing Machine
• Along with the vacuum cleaner, one of the first appliances to find its way into the American home was the clothes washing machine. Of the many mundane tasks of daily life, laundering clothes was for centuries one of the more labor-intensive tasks. Primarily women’s work, clothes were washed by hand by scrubbing them against a
hard surface—first a rock and then a ribbed washboard (invented in 1797).

- Given the onerous nature of the work, inventors dating back to England in the 1690s contemplated making a machine for washing clothes. As with other efforts to mechanize a task, most inventors tried to make a machine that imitated a human hand rubbing clothes against a washboard.

- Although crude washing machines were available in the 19th century, few American homes acquired one. Laundry was either still done by hand at home or, increasingly, at commercial steam laundries.

- Beginning in the late 1840s, perhaps as a result of the gold miners needing someone to wash their clothes in San Francisco or to provide clean linen to the growing number of hotels in other cities, entrepreneurs set up commercial laundries. In response, inventors developed large-scale washing machines powered by steam engines.

- By 1900, there were commercial laundries in cities and towns across the country, and many families took advantage of this service. If
they did not send all of their laundry out for washing, families at the very least sent out men’s shirts, bed sheets, and table linens.

- Hence, when manufacturers turned to selling washing machines in the 1920s, they were in the curious position of having to convince American housewives to move a service performed outside back into the home. With a washing machine at home, the housewife could do laundry whenever she wanted; she was no longer at the mercy of the schedule of a commercial service.

- But to sell convenience, manufacturers realized that they would need to automate the laundry process. All of the steps of washing clothes—filling the tub with soapy water, agitating the clothes, rinsing with clean water, and wringing out the excess water—needed to be simplified and mechanized.

- Just as they had done in developing industrial systems, engineers had to break washing clothes down into its component steps and analyze how each step could be done by machine.

- In pursuit of automation, washing-machine manufacturers first replaced hand cranks with electric motors. In the earliest electric washing machines, one motor did two jobs: First, it agitated the clothes in the washtub; then, the housewife switched it and used it to turn the wringer on the top of the machine.

- In the 1920s, Howard Snyder, a talented mechanic at Maytag, designed the vaned agitator mounted on the bottom of the washtub. Rather than slapping the clothes around, the agitator now forced soapy water through the clothes. Although better, these washing machines still required the housewife to remove the rinsed clothes from the tub and pass them through the wringer.

- In the late 1930s, engineers eliminated the wringer by introducing a two-speed motor and a perforated basket inside the washtub. While the low speed was used for washing, the high speed spun the perforated basket and eliminated excess water in the clothes
by centrifugal force. Finally, engineers designed a timer and electromechanical controls that opened and closed the water supply and adjusted the motor’s speed.

- All of these steps took time to work out and were delayed by World War II. Maytag, for instance, produced no washing machines during the war and instead manufactured aircraft parts. It was not until 1947 that the Whirlpool Corporation introduced the first fully automated washer, and it was at this point that washing machines assumed their modern boxy shape.

- In the meantime, American housewives eagerly purchased the first semiautomated machines. In 1926, Americans purchased 900,000 machines, but in 1935, they bought 1.4 million. As demand grew, manufacturers employed mass-production techniques, and like Ford, they were able to drive down production costs and retail prices.

- While the average machine cost $150 in 1926, the price had dropped to $60 in 1935. Not only did Sears and Ward’s sell washing machines to consumers, but department stores also began selling them in the 1920s. In addition, new retail chains appeared in several regions, specializing in selling domestic appliances.

- Through the 1940s and 1950s, the washing machine was followed by other laundry-related improvements, including the clothes dryer, better detergents, and wash-and-wear clothes that required no ironing. However, while all these improvements were touted as being more convenient—in the sense that the housewife had control over the laundry process—these changes did not translate to saving time for the housewife.

- Surveys revealed that while women spent five hours per week on laundry in 1925, by 1964, they devoted six hours per week to this chore. In all likelihood, this increase in time was a result of Americans having more changes of clothing as well as higher expectations about cleanliness. Thus, instead of making life easier
for the housewife, the combination of the washing machine and rising expectations actually created more work for her.

Suggested Reading

Cowan, *More Work for Mother*.

Giedion, *Mechanization Takes Command*.

Questions to Consider

1. What does it mean to call a society a “consumer” society?

2. What were the technical and cultural reasons for why the first vacuum cleaner invented by Herbert Cecil Booth had to come into the home through the window?

3. As a result of appliances, does the modern housewife spend more or less time working to maintain a home? Why?
Across the 20th century, electronics has grown up around three key inventions: the vacuum tube, the transistor, and the integrated circuit (or chip). Notably, as you will learn, each of these inventions was a dramatic step forward, building on the ideas and practices of the previous device. Because electronic components can perform several simple functions—such as generate and detect radio waves, amplify weak signals, and operate as switches—it became possible to build radios, televisions, computers, and cell phones.

The Vacuum Tube

- As late as 1912, while Marconi had made many improvements in his radio equipment, he was still using a crude receiver to detect incoming signals—a coherer that consisted of iron filings in a tube. Incoming radio signals made the filings line up in the tube and conduct an electric current to a sounder, which produced either a short or long click (a dot or a dash) in the headphones. After each incoming signal, the coherer would have to be cleared by being gently tapped by a tiny hammer.

- To replace this complicated detector, two inventors—John Ambrose Fleming with British Marconi and an American named Lee de Forest—experimented with modified incandescent lamps.

- Several decades earlier, Edison had inserted a metal plate inside one of his light bulbs, and he noticed that when a current was run through the bulb’s filament, another current was induced in the metal plate. Edison didn’t do anything with the phenomenon he observed, but it was dubbed the “Edison effect” in the scientific literature.

- After designing the transmitting station that Marconi used to send his first signal across the Atlantic in 1901, Fleming began studying the Edison effect and found that specially designed lamps—which
he called vacuum tubes—could function as a switch because the current would only flow in one direction through them, making them what we would call a diode. Equally, Fleming noticed that vacuum tubes could also be used to detect radio waves and might be used as a replacement for Marconi’s coherer.

- Following up on Fleming’s work, de Forest added a third element to his bulb—a small wire grid that could carry its own current—and found that his bulb could operate not only as a wave detector, but also as an amplifier. De Forest called his bulb the Audion. One of the first companies to take a license from de Forest for the Audion was AT&T.

- Edwin Howard Armstrong studied vacuum tubes and invented several practical circuits that were able to detect, tune, and amplify radio signals so that it was possible to have a convenient radio receiver in the home. Hence, the vacuum tube was at the heart of the radiobroadcasting boom of the 1920s.

As an invention, the vacuum tube is one of the building blocks of the 20th century.
• From the 1920s to the 1950s, vacuum tubes were high tech and could be found in many of the most amazing devices of those decades, such as radars. Engineers tried using them to build large-scale computers.

• Vacuum tubes, like light bulbs, have a relatively short service life and fail. They are also fragile like light bulbs. They use a lot of current and generate a great deal of heat. Hence, a substitute was needed—a device that could function much like a vacuum tube but at the same time didn’t have all of these problems.

The Transistor

• The substitute for the vacuum tube was the transistor—_invented at Bell Labs, the research arm of AT&T. To overcome the limitations of the vacuum tube, engineers and physicists at Bell Labs began investigating alternatives as early as the 1930s.

• They were prompted to do so by the leader of Bell Labs, Mervin Kelly. Intent on eliminating vacuum tubes and mechanical relays from AT&T’s telephone network, Kelly encouraged his researchers to investigate nonmechanical, nonthermal ways to control electric currents.

• Physicists at Bell Labs focused on how semiconductor materials (such as germanium or silicon) responded to electric currents passing through them. As its name suggests, a semiconductor has electrical properties that fall between a conductor (like copper, in which an electric current flows freely) and an insulator (in which current will not flow).

• One of Bell Labs’ leading researchers on semiconductors was William Shockley, but he was initially unable to come up with a working device. Instead, in 1947, John Bardeen and Walter Brattain discovered that one could control currents at the point where two kinds of semiconductor materials were joined.
Jealous that he had to share credit for the invention of the transistor with Bardeen and Brattain, Shockley went on to invent in 1949 an improved transistor, the junction transistor, which consists of two different semiconductor materials sandwiched together. In particular, engineers at Bell Labs developed ways to add impurities to silicon so that it had exactly the right semiconductor properties.

Bell Labs patented these two transistor designs and then sold licenses to other electronics companies. By 1953, transistors could be found in hearing aids and miniature radios, and in 1957, the first transistorized computers were introduced by Philco and UNIVAC.

The Integrated Circuit

As important as the transistor was, it was eclipsed by another breakthrough in semiconductor electronics: the integrated circuit or chip. This idea was first investigated by Jack St. Clair Kilby at Texas Instruments, who demonstrated in 1958 that one could make a miniature circuit using only silicon.

Kilby was concerned by what electronics engineers referred to at that time as the “tyranny of numbers.” They could see how hundreds or thousands of transistors could be used to create computers and other complex electronic devices, but they were frustrated by the fact that to create these circuits, workers had to connect each component in the circuit by hand soldering.

The tyranny of numbers referred to the reality that the more complex the circuit, the harder it was to fabricate. Although engineers eliminated some of this handwork by creating printed circuit boards and automatic soldering machines, the reliability of circuit boards was still very low, and electronic devices remained expensive.

To overcome the tyranny of numbers, Kilby thought, “If you could create a substitute for the vacuum tube using a semiconductor material, why not create a semiconductor substitute for an entire electronic circuit?” Kilby tested this idea by making the first integrated circuits by soldering tiny pieces of germanium together.
Texas Instruments promptly filed patents in 1959 to cover Kilby’s invention. In 1961, Texas Instruments built the first computer using integrated circuits for the U.S. Air Force, and Kilby went on to help develop the first handheld electronic calculator in 1967, the first consumer product to utilize integrated circuits or chips.

Meanwhile, in California, the chip was undergoing parallel development. Shockley moved to California in 1955 to create his own company, the Shockley Semiconductor Laboratory, and he attracted a team of very bright engineers and physicists. However, his erratic behavior quickly put them off, and in 1957, eight of his best people quit and created their own semiconductor company.

Supported by Sherman Fairchild, the “traitorous eight” (as they called themselves) set up Fairchild Semiconductor. Heading up this company was Robert Noyce, who advocated that the new company focus on developing new transistor designs using silicon.

To do so, another member of the eight, Jean Hoerni, created the planar process, whereby semiconductor material could be laid down layer by layer. Using photographic techniques, a pattern could be put down on each layer, and acid could then be used to eat away the undesired material.

As Hoerni’s process took form, Noyce realized that you could not only use this method to make transistors but also entire circuits, and he came to this realization about the same time as Kilby at Texas Instruments. Hence, both men are regarded as coinventors of the chip.

Because they were lightweight, highly reliable, and consumed little power, integrated circuits were taken up by the U.S. military and NASA for use in missiles and spacecraft. For all the same reasons, IBM decided to use first ceramic modules and then integrated circuits to build a large-scale, general-purpose computer (now known as a mainframe).
The Microprocessor

- Just as the traitorous eight had left Shockley Semiconductor in 1957, talented people—sometimes known as the fairchildren—left Fairchild Semiconductor in the 1960s to create many of the companies that constitute Silicon Valley. Among the last to leave were Noyce and Moore who set up their own business, Intel.

- Casting around for customers, Intel entered into an agreement with a Japanese company, Busicom, to develop an electronic calculator to compete with Texas Instrument’s new handheld model. Assigned to design the necessary chips for the Busicom calculator was a young engineer named Marcian Edward “Ted” Hoff.

- Disturbed by the undue complexity of Busicom’s chip design, Hoff instead proposed to Noyce that Intel design a series of standard chips that could perform the basic functions of a computer: There would be chips for read-only memory (ROM); another for random-access memory (RAM); and a final one for doing the actual calculations, the microprocessor. These three chips might do everything that existing minicomputers that cost thousands of dollars could do.

- Hoff and his associates at Intel soon saw that a microprocessor and memory chips like this represented a giant change in their industry. If they could come up with a standardized, flexible design, they could shift the entire industry from batch mode to mass production, and Intel could manufacture and sell millions of chips and drive down the cost per chip.

- It took Hoff and his colleagues several years to convince Noyce and others at Intel to see that this business model would work. It also took some serious effort to match the circuitry in the chip with the software that would run on it. But Hoff pushed ahead, and Intel started shipping in 1971 the first commercial microprocessor, the 4004, which contained the equivalent of 2,300 transistors.

- By placing an entire computer on a chip (known as a microprocessor), it became possible not only to design personal
computers, but to also integrate computers into a wide variety of other applications, such as automobile controls, cameras, answering machines, and medical monitors.

- More than just improving existing technologies, the chip has created entirely new products. Without chips, there would be no CD or MP3 players, global positioning system devices, or cell phones.

**Suggested Reading**

Gertner, *The Idea Factory*.

Berlin, *The Man behind the Microchip*.

Moore, “Cramming More Components onto Integrated Circuits.”

Reid, *The Chip*.

Zygmont, *Microchip*.

**Questions to Consider**

1. What is the difference between an electrical and an electronic device?

2. What was the “tyranny of numbers,” and how did it limit the development of electronics in the 1950s?

3. Why is the invention of the microprocessor just as important as the invention of the integrated circuit?
As you will learn in this lecture, two technologies—communications satellites and cellular telephones—have been combined with digital information, making it possible by the late 1990s to communicate with nearly every part of the planet. By the close of the 20th century, there were hundreds of satellites circling the Earth that were used not only for communications but also for weather, Earth imaging, military communications, and global positioning. In addition, according to a 2012 survey, around half of the U.S. mobile consumers own smartphones and could account for around 70 percent of all U.S. mobile devices by 2013.

Communications Satellites

- Prior to satellites, international telephone service was provided by undersea cable or short-wave radio transmission, both of which were expensive and offered little bandwidth (i.e., the capacity to carry multiple signals simultaneously). During the 1960s, communications satellites changed this.

- Communications satellites provide television, telephone, and data services between two widely distant locations. They operate within a system in which signals are transmitted using microwaves from an Earth-based station to the satellite (known as the uplink); the satellite then amplifies the signals and retransmits them to a receiving station located at another point on Earth (the downlink).

- Nearly all communications satellites are in geostationary orbit at an altitude of 22,300 miles (35,900 km). At this height, the satellite’s period of rotation is the same as the Earth’s period of rotation, so the satellite stays over the same spot on the globe.

- The idea of using satellites to relay radio signals around the world was first proposed in 1945 by the science-fiction writer Arthur C. Clarke, who thought that satellites in geostationary orbit could be
used to transmit messages from station to station and to expand radio broadcasting.

- The space age began in 1957, when the Soviet Union launched Sputnik I, a basketball-sized satellite that orbited the Earth for three months. The United States responded by launching several satellites of its own, including Echo I, which consisted of a large mylar balloon coated with a thin layer of aluminum, and radio signals were bounced off of its surface.

- The first satellite that could receive and retransmit television and telephone signals was Telstar I, launched in 1962. Telstar was succeeded by several generations of satellites launched by the International Telecommunications Satellite Organization (Intelsat).

- While Intelsat I, launched in 1965, could handle 2,400 voice channels, ninth-generation satellites launched in the early 2000s carried 600,000 telephone calls or 600 television channels. By the 1990s, Intelsat was operating 15 satellites that could beam television programs and provide telephone service anywhere in the world.

- In 1970, the Soviets launched their own communications satellite, Molniya. Since then, other nations have placed satellites in orbit, including Canada, Indonesia, India, Japan, the European Union, France, Brazil, the Arab League, Australia, Mexico, China, and Britain.

- By the end of the 1970s, satellites were transmitting television programming to all parts of the globe, and they were carrying over two-thirds of all international telephone calls.

- Beginning in the 1980s, however, the introduction of high-capacity fiber-optic cables has meant that more telephone service is once again being provided by undersea lines.
Cell Phones

- Along with satellites, global communications have been greatly affected by the development of cellular telephones, which use radio waves to communicate with a base station that in turn routes calls from the sender to the recipient.

- While Marconi and his companies concentrated on using Morse code to send messages, his rival, Reginald Fessenden, experimented as early as 1906 with transmitting speech via radio waves.

- During the 1920s, RCA provided a variety of radiotelephone services, and by 1930, telephone customers in the United States could be connected by radio to a passenger on an ocean liner in the Atlantic Ocean.

- During World War II, the Army contracted with the Galvin Manufacturing Corporation of Chicago (soon to become Motorola) to manufacture radiotelephones for use by troops in the field. Motorola produced two models: a Walkie-Talkie (which consisted of a radio in a backpack) and a Handie-Talkie (which could be held in one hand). Both relied on vacuum tube technology and high-voltage dry cells.

- After the War, AT&T was looking for new markets, and it introduced mobile telephone service for use in automobiles. The required equipment weighed about 80 pounds and took up a fair amount of trunk space. Subscriber growth was limited by the technology; because only three radio channels were available, only three customers in any given city could make mobile telephone calls at one time.

- Even though AT&T’s mobile telephone service was the only service available until the 1970s, engineers at Bell Labs were quick to recognize the limitations of the system. As early as 1947, they proposed laying out a network of hexagonal cells for mobile phones in vehicles, but the necessary electronics were not developed until the 1960s by Richard H. Frenkiel and Joel S. Engel at Bell Labs.
With the existing system, a car with a mobile phone had to stay within the coverage area serviced by one base station during the duration of the phone call; in other words, there was no way to hand off a call as the car moved out of one cell and into another. In 1970, Amos E. Joel at Bell Labs perfected an automatic call handoff system that allowed mobile phones to move through several cell areas during a single conversation without interruption.

But while engineers had now come up with a way that mobile phones could “roam,” they still hadn’t solved the problem of how to increase the number of users, and more users would be needed if it was going to economically feasible to build a regional or national cell phone network.

Because there isn’t enough space on the radio spectrum for each cell-phone user to have his or her own frequency, engineers decided that they would reuse frequencies. Rather than assigning a single frequency to each phone, they would assign a group of frequencies that would be used by the whole system. When a call is placed, the phone system picks an open frequency for that call and makes the connection.

With a cellular system, frequency reuse made a great deal of sense because, for a given call, the system could assign it not only the frequencies available in one cell, but also hand the call off to other open frequencies as the caller moved to another cell. Remarkably,

These days, it’s difficult to even know how to use all of the functions that cell phones are capable of.
computers handle these changes so smoothly that users seldom notice that these changes are happening.

- All that remained was to create a portable phone that could operate outside of an automobile. Both Motorola and Bell Labs raced to be the first to produce a handheld mobile phone. Drawing on its experience with walkie-talkies and pagers, Motorola won that race, and on April 3, 1973, Motorola researcher Martin Cooper used the first portable phone to call Joel Engel at Bell Labs.

- This first handheld phone used by Dr. Cooper weighed 2.5 pounds and measured 9 inches long, 5 inches deep, and 1.75 inches wide. It offered a talk time of just 30 minutes and took 10 hours to recharge.

- The first cellular telephone network was established in Japan in 1979, and a second early system was deployed in Denmark, Finland, Sweden, and Norway in 1981. The first network in the United States was set up by AT&T and Motorola in 1983 to serve the Chicago area; this network grew from 200,000 subscribers in the first year to 2 million users five years later.

**From 1G to 4G**

- The first cell networks relied on analog signal processing, using separate frequencies, or “channels,” for each conversation. They therefore required considerable bandwidth for a large number of users. These systems were also unencrypted, meaning that not only could people eavesdrop on cell phone calls using a police scanner, but they could also hack into the system and make free calls.

- In response, telecommunication engineers developed a second-generation (2G) protocol that utilized digital signal processing. After using several different techniques, American cell phone networks settled on a combination of digital voice compression with digital modulation, a technique known as code-division multiple access (CDMA). By increasing the capacity of the existing cell phone network by 10 to 20 times and, hence, reducing the cost
of individual calls, CDMA has had an important impact on the development of cell phones.

- Other multiplexing techniques were developed by other countries, including the digital global system for mobile communications (GSM) by the European Community in 1988. Since then, most of the world has adopted GSM, but the United States has continued to use CDMA, with the result that American cell phones are not able to connect with foreign cell networks.

- With 2G came new features like text messaging, which was first introduced in the United Kingdom in 1992, as well as SIM cards, which could be used to transfer the identity of a user and his or her account from one phone to another.

- Coinciding with the introduction of 2G systems was a trend away from the original larger phones toward smaller phones. These new phones took advantage of both more advanced batteries and more energy-efficient electronics.

- As 2G phones became more commonplace, cell phone companies began to explore how they could provide not only telephone but also data services. In particular, the companies realized that people could get their email delivered to their phones, but to do so would require greater data speeds than could be provided by the existing 2G service.

- In response, the industry developed the next generation of technology, known as 3G. The main technological difference between 2G and 3G is that 3G uses packet switching for data transmission. This technology was launched first in Japan and Europe in 2001 and then in the United States in 2002.

- While 3G networks offered the possibility of streaming video, such as television shows or YouTube videos, telecommunications companies have assumed that the market will only grow by increasing data transmission speeds. Hence, starting in 2006, the
industry began developing data-optimized fourth-generation (4G) technologies, with the promise of speed improvements up to tenfold over existing 3G technologies.

**Suggested Reading**

Agar, *Constant Touch*.

Gertner, *The Idea Factory*.

**Questions to Consider**

1. What is the “handoff,” and why was it a critical invention in the development of the cell phone?

2. Why does an American cell phone not work in Europe and other parts of the world?

3. Why are cell-phone innovations frequently introduced first in Europe and Japan rather than the United States?
While it appeared revolutionary in the 1980s, Steve Jobs (and others) introduced the personal computer by capitalizing on a series of trends in American life that dated back over a century and technological trends with an even longer provenance. As you will learn in this lecture, it is difficult to find a point at which the evolution of personal computing “mutates” in a way that produces a true discontinuity—each step builds on preexisting technology. Although that technology was often repackaged or reconfigured or redirected to a new purpose, even those purposes remained new expressions of old tasks or functions.

The First Electrical Computers

- In the early 18th century, Gottfried Leibniz discussed the potential of computing the four basic mathematic operations using only addition, suggested the representation of information beyond numbers, and even described a computing machine based on binary numbers that used marbles in much the same way that modern computers use electrons to represent binary numbers.

- In the 1830s and 1840s, Charles Babbage designed and built parts of an Analytical Engine based on the decimal system. Although Babbage chose to base his machine on proven technology—for example, it was powered by steam rather than electricity—it had all the basic components of the modern electronic computer.

- Ada Lovelace, a student of mathematics and the daughter of Lord Byron, understood what Babbage did not—that the machine could do more than mathematics because numbers could represent other symbols, letters, or even musical notes.

- Certainly with some relation to the invention of the telegraph (1844), telephone (1876), electric light (1880), electric motor (1886/1888), and the general availability of electrical power, at least
in urban areas, a symbiotic burst in business machine innovation and big business formation occurred in the United States between the end of the Civil War and the turn of the 20th century.

- It would be up to John von Neumann to “reinvent” Leibniz’s notion of digital binary computing. During and after World War II, von Neumann built on the earlier ideas of Alan Turing (algorithmic computing) and Lewis Richardson (massive cellular arrays) and worked on the development of electronic computers to support research into atomic fission and the atomic bomb.

- One of the most influential roles in the process of reconceptualizing the machine was played by a woman named Grace Hopper, who understood the need to distinguish between machine function and data processing. She also knew that in order for the limited-memory machines of the day to run efficiently, instructions originally composed in a high-level programming language needed to be rewritten into compact low-level machine code. This process was inefficient and prone to error.

- As a solution, in the early 1950s, Hopper developed the first computer compiler programs, which converted source code from the programming language into binary machine code. Most people thought this was an impossible task, and the Navy refused to authorize the project, and many refused to use it even after it was proven.

- More importantly, by simplifying programming and componentizing program functions, Hopper made computers much more efficient and flexible—a huge step toward rejecting the model of the past and developing general-use computers, where hardware would be generalized and software specialized.

- Hopper also helped develop the programming languages COBOL and Fortran, which made generalized computing viable, and then later in life, she lobbied the Department of Defense to adopt a wide array of hardware, software, and communications standards
designated to foster distributed computing with access to central data repositories—the very model of contemporary computing.

- The first commercial computer to truly exploit Hopper’s vision of a general-use machine was the IBM 360, released in 1964. The “360” designation was intended to imply that the machine could be utilized to perform a full array of functions—covering 360 degrees of the business universe. The concept and the product were so successful that IBM sold more than 1,000 machines in the first 30 days it was on the market.

- At this point, “general use” and “standard” were two very different concepts. While the 360 utilized some standard communications protocols, it was at its heart a proprietary piece of hardware that depended on a proprietary operating system. It would be 15 years before IBM took the first step toward a more open, standard system profile with the outsourcing to Microsoft of the development of an operating system for its x86-based personal computers.

- Two other cultural phenomena occurred during this period of gestation that helped open up public attitudes to the approaching wave of personal computing. First, while the success of the IBM 360 was based primarily on the desire of corporations to impose centralized control on business processes, it engendered a sense of computerization as a requirement of competitiveness, making it a requirement of doing business. As the eventual equation of computing with “cool” took hold in their professional lives, people started to take that attitude home with them.

- Secondly, nowhere did this image of them seem more appropriate than in the world of software development. With the clear delineation of function between hardware and software, and the further distinction between routine operating system and creative software application development, computer software entered a new, more amorphous realm.
The Graphical User Interface and Apple

- The development of integrated circuits for all aspects of computing during the 1960s and 1970s was a prerequisite for personal computing—for miniaturization as well as reliability. Their development, however, was not a function of the development of personal computers; rather, it was a precondition for person computers.

- The solution to the other hurdle, usability, was the development of the graphical user interface (GUI). This is often understood to be a result of the development of personal computers, specifically the work done by Apple. However, the initial design and development of this feature—one that is such an iconic characteristic of the field—actually predates the founding of Apple.

- In 1970, Xerox opened its Palo Alto Research Center (PARC) and staffed it with some of the corporation’s brightest minds. An advanced research facility with a broad charter to develop a range of technologies, PARC invited a number of visiting scholars from the Stanford University Artificial Intelligence Laboratory, including Jef Raskin.

- It took three years (a relatively short time, given the magnitude of the task) for PARC to develop a GUI and a machine to run it on—the Alto, which is seen by many as the world’s first personal computer. It was certainly the world’s first computer operated with a keyboard and mouse using a graphical user interface. It also connected to other Altos using a new network method: ethernet.

- For whatever reason, perhaps because it was seen as a distraction from the main business of making copiers, Xerox chose not to bring it to market. It would be two more years (1975) before Steve Wozniak even designed and built the Apple I and Apple II computers.

- The birth of those machines did lead to the formation of Apple Computer, Inc., in 1977, and two years later, Apple began working
on its own GUI. When they did, one of the key contributors was Jef Raskin, an Apple employee. Over the course of the next three or four years, Apple struggled to develop the LISA, a machine intended to be somewhat of an “Alto+.”

- In 1981, Raskin wrote a memo detailing his work on the LISA and Macintosh projects that specifically states the degree to which he drew on preexisting Xerox technology. While Apple had made progress on its own GUI, it has to be recognized that what they did up to that point was a direct descendant of the work done at PARC. Furthermore, within a year, 15 PARC employees jumped ship in favor of Apple.

- Still, it would not be fair (or accurate) to say that Apple failed to provide innovation in technical design and development of personal computing. On the other hand, it must also be said that what Apple provided in abundance was what Xerox lacked: the corporate vision, will, and energy to bring technology to market and to popularize it beyond nearly anyone’s imagination. In many respects, this was—and still is—Apple’s real creative genius.

**IBM and Microsoft**

- It was during this same period that IBM threw its might into the personal computing wars. The IBM PC was introduced in 1981 with a price point below $1,500, and within two years, they were selling their one-millionth machine, despite its dependence on a DOS-based command-line interface supplied by Microsoft.
• However, even the volume of sales by IBM and its clones could not mask the consumer appeal of the GUI, and in 1983, Microsoft announced its plans to develop and release Windows.

• Their efforts proved no more efficient than Apple’s: It was five years before they finally released a workable version of the Windows operating system in 1988—15 years after Alto first saw the light of day at PARC. Most observers saw Windows as being inferior in design and functionality to Xerox’s GUI (which had been enhanced periodically over the intervening years).

• Prior to this, in 1984, Microsoft introduced MS Word, which was one of a series of early “killer apps” that included spreadsheet applications such as VisiCalc (1979) and Lotus-123 (1983), and Excel (1985), as well as other word-processing applications such as WordStar (c. 1985).

• Aldus PageMaker (1985) and Quark Xpress (1987) took word processing to another level and led to an entirely new genre: desktop publishing. Deluxe Paint, a bitmap editor, was the first released in 1985, and Photoshop first appeared in 1988, although neither bears much resemblance to any graphic editor available today. Beyond spreadsheet applications, nearly all of these early applications simply computerized preexisting manual or machine tasks.

• While a broader catalog of applications wooed buyers, it did not enable personal computing to revolutionize business processes or lifestyle management. If revolutionary changes have occurred in these areas more recently, that is much more a result of Internet connectivity, not personal computing.

• While gaming is a pastime of many current PC users, early PCs lacked the processing and graphics capacity of purpose-built game consoles such as Atari, Nintendo, and Sega. Today, the Sony PlayStation, Wii, and Xbox retain a noticeable advantage over general-purpose personal computers.
In many ways, this underscores a new trend that reverts to an earlier path: As the functional universe expands, personal computing is growing increasingly dependent on purpose-built hardware.

**Suggested Reading**

Beyer, *Grace Hopper and the Invention of the Information Age.*

Ceruzzi, *Computing.*

Isaacson, *Steve Jobs.*

**Questions to Consider**

1. Why was the invention of programming more important than the development of hardware for the evolution of computers?

2. Why do you think that Xerox failed to exploit the graphical user interface and instead let Steve Jobs and Apple use it to capture the personal computer market?

3. Like other inventions, how was the personal computer shaped by the time and place it was first developed?
Genetic engineering is the direct manipulation of an organism’s hereditary information (or genome) by introducing foreign DNA or synthetic genes into the organism under study. Genetic-engineering techniques have been applied in agriculture, medicine, and criminal forensics. In this lecture, you will learn about the basic technique underlying DNA analysis—polymerase chain reaction (PCR)—as an introduction to the innovations that have taken place in the last 30 years in genetic engineering and biotechnology. Perhaps the most dramatic application of genetic engineering has been the cloning of new animals, including knockout mice and transgenic mice.

Genes and DNA

- Genes are how living organisms transmit features from one generation to the next. Genes are made from a long molecule called deoxyribonucleic acid (DNA), which is copied and inherited across generations. DNA can be found in the nucleus of every cell in an organism.

- The DNA molecule takes the form of a double helix, which looks like a twisted ladder, with the key parts being the rungs of the ladder. Each rung consists of nucleotides—guanine, adenine, thymine, and cytosine—which pair up in particular ways.

- Different pairs of these nucleotides on each rung of the ladder encode the information that the cell uses to make proteins, which in turn cause other things to happen in the organism, like how the cell processes other chemicals or, at the level of the whole organism, produces traits like the color of your hair.

- DNA was first isolated in 1869 by a Swiss physician, Friedrich Miescher, who was studying the microscopic substances he found
in pus on discarded surgical bandages. Because the substances came from the nuclei of the cells, Miescher called them nuclein.

- In 1919, Phoebus Levene at the Rockefeller Institute identified the base, sugar and phosphate nucleotide unit, that made up DNA. Levene suggested that DNA consisted of a string of nucleotide units linked together through the phosphate groups, but neither he nor other biologists could quite determine the structure of DNA or how it worked.

- In 1927, Nikolai Koltsov speculated that inherited traits could be inherited via a “giant hereditary molecule” made up of “two mirror strands that would replicate in a semi-conservative fashion using each strand as a template.”

- In 1953, working from an X-ray diffraction image of the DNA molecule, James D. Watson and Francis Crick identified the structure as a double helix. Once they knew that DNA took this form, Crick was able to explain how DNA passed instructions (and, hence, genetic information) to the cell.

- Watson and Crick’s discovery revolutionized biology, shifting interest away from whole organisms to an intense focus on the molecular mechanisms that operated within the cell. From the 1950s to 1980s, molecular biology and genetics grew rapidly as fields, contributing to our understanding of how many diseases function, and also led to the development of new drug treatments.

- In addition, molecular biologists perfected techniques for isolating specific pieces of DNA that could either be inserted into the cells of organisms to change how these organisms function—which is known as recombinant DNA—or they could create new plants and animals without having to use natural reproduction processes—which is known as cloning.

- Both of these techniques set the stage for the creation of an entirely new industry—biotechnology—which it was hoped could create
better plants, animals, and drugs for use in the agriculture industry and medicine.

- One of the first companies in the biotechnology field was Cetus Corporation, located in Emeryville, California. Founded in 1971, Cetus sought to create automated methods selecting industrial microorganisms that could produce greater amounts of chemical feedstocks, antibiotics, or vaccine components. However, as the company became proficient in genetic-manipulation techniques, it turned to creating new drugs for treating cancer.

**Photocopying DNA: PCR**

- Sometimes referred to as “molecular photocopying,” the polymerase chain reaction (PCR) can characterize, analyze, and synthesize any specific piece of DNA or RNA. It works even on extremely complicated mixtures, seeking out, identifying, and duplicating a particular bit of genetic material from blood, hair, or tissue specimens from microbes, animals, or plants, some of them many thousands—or possibly even millions—of years old.

- As a technique, PCR was invented by a biochemist, Kary B. Mullis, in the 1980s, and he was awarded the Nobel Prize in Chemistry for it in 1993. In the early 1980s, Mullis was hired by Cetus, which is where he eventually came up with the PCR procedure. While the basic idea for PCR came from Mullis, the reduction of Mullis’s idea to practice was done largely by others.

- PCR requires a template molecule—the DNA you want to copy—and two primer molecules to get the copying process started. The primers are short chains of the four nucleotides that make up any strand of DNA.

- Unlike DNA, which has two strands that twist around each other, primers are single stranded. They consist of a string of nucleotides in a specific order that will, under the right conditions, bind to a specific complementary sequence of nucleotides in another piece of single-stranded DNA.
• For PCR, primers must be duplicates of nucleotide sequences on either side of the piece of DNA of interest, which means that the exact order of the primers’ nucleotides must already be known. These flanking sequences can be constructed in the lab or purchased from commercial suppliers.

• Starting from the primer, the polymerase can read a template strand and match it with complementary nucleotides very quickly. The result is two new helixes in place of the first, each composed of one of the original strands plus its newly assembled complementary strand.

• All PCR really requires in the way of equipment is a test tube, reagents, and a heat source, but because different temperatures are optimal for each of the three steps that are involved in the PCR process, machines now control these temperature variations automatically. To get more of the DNA you want, just repeat the process, beginning by denaturing the DNA you’ve already made. The amount will double every time.

Genes are made up of DNA, which is known for its double-helix structure.
• With the cycle of rapid heating and cooling controlled automatically, nature—aided by scientist-supplied primers, polymerase, nucleotides, and chemical reagents—does the rest. Each cycle takes only one to three minutes, so repeating the process for just 45 minutes can generate millions of copies of a specific DNA strand. Once the primers have been characterized and obtained, PCR can do in a week the work that used to take a year.

• Medical research is profiting from PCR mainly in two areas: detection of infectious disease organisms; and detection of variations and mutations in genes, especially human genes.

• Because PCR can amplify unimaginably tiny amounts of DNA (even the DNA from just one cell), physicians and researchers can examine a single sperm or track down the elusive source of a puzzling infection. These PCR-based analyses are proving to be just as reliable as previous methods—sometimes more so—and often much faster and cheaper.

• PCR’s ability to identify and copy the tiniest amounts of even old and damaged DNA has proven exceptionally valuable in the law, especially criminal law. PCR is indispensable to forensic DNA typing, commonly called DNA fingerprinting.

• Although in its early days DNA fingerprinting was controversial, laboratory procedures have now been standardized, and carefully done DNA typing is now accepted as strong evidence in courts throughout the world.

The Genetically Engineered Mouse
• Along with the DNA fingerprinting used in criminal investigations, the other way that most of us are familiar with genetic engineering is through the cloning of new animals. For example, Dolly the sheep was identical to her mother and was created by Scottish researchers in 1996 through cloning. As impressive as Dolly was, the first important animal that was cloned and patented were the mice that are now used for medical research.
While biomedical scientists do use sophisticated computer models to predict the behavior of new drugs, it is still necessary to study how these new drugs function in a live animal—only by doing so can scientists fully understand how the drug operates and what the possible side effects might be.

However, to develop new drugs, you want laboratory animals with several characteristics. It’s good if they are small and if they have a relatively short life cycle; it’s for these two reasons that early genetics researchers worked with fruit flies (they also manifest genetic mutations in highly visual ways).

However, most importantly, you want an animal that is well characterized and whose characteristics don’t change from generation to generation; in other words, you want a stable animal model for your research.

The first genetically modified mouse was invented in 1974 when Rudolf Jaenisch and Beatrice Mintz at MIT inserted a DNA virus into early-stage mice embryos and showed that the inserted genes were present in every cell when the mice were born. However, these mice did not pass on the inserted genes to their offspring.

In 1981, Frank Ruddle at Yale and Frank Constantini and Elizabeth Lacy at Oxford injected purified DNA into a single-cell mouse embryo and demonstrated that the genetic material was transmitted to subsequent generations. Through the 1980s, these techniques were standardized so that it became possible to produce mice with characteristics needed to conduct experiments related to cancer and other diseases.

Genetically modified mice today typically come in two forms. First, there are knockout mice, in which the activity of one or more genes has been turned off. These mice are used to study obesity, heart disease, diabetes, arthritis, substance abuse, anxiety, aging, and Parkinson’s disease. Second, there are transgenic mice, which carry cancer-causing genes (oncogenes). Hundreds of different transgenic
mice have been developed in order to study the cancers affecting most organs in the human body.

- Perhaps the most famous cancer-fighting mouse is the OncoMouse, which was designed by Philip Leder and Timothy A. Stewart at Harvard. Leder and Stewart sought to have this mouse patented in the United States, Canada, and the European Union, and the case has prompted much legal discussion about whether a life form can be patented. DuPont currently owns the rights to OncoMouse.

- Although there are many critics of genetic engineering, genetically modified mice are a key tool used by scientists today to study disease and develop new drugs and therapies. Because DNA is now seen as “program” that “runs” an organism, biologists and computer scientists often work together, and these collaborations should result in significant improvements in our understanding of human health.

Suggested Reading

Powledge, “The Polymerase Chain Reaction.”

Wade, “Scientist at Work/Kary Mullis.”


Questions to Consider

1. Based on Watson and Crick’s pioneering work on how DNA works, does it make sense to say that biology today is an “information” science?

2. What are the benefits of DNA fingerprinting, and do they outweigh the ethical risks?

3. Why do medical researchers need a genetically engineered mouse?
How did the idea of the Internet and the World Wide Web go from being a fanciful idea put forward by Nikola Tesla in 1902 to being the incredibly important invention that it is 100 years later? As you will learn in this lecture, the journey from Tesla’s idea to the Web, which takes us from Bell Labs to academic computer science departments, involves some of the most powerful inventions of the 20th century—the idea of digital information and packet switching.

From Analog to Digital, From Communication to Information

- In analog communications, information is stored or transported from one place to another by the creation of a representation that serves as an analog of the message. For example, radio and television work by converting sound and images into radio waves that are sent over the air from the transmitter to the receiver.

- In the early 1900s, Nikola Tesla anticipated that he would send messages through the Earth by assigning a unique frequency to each message. Of course, this meant that he would soon use up all of the frequencies in one portion of the electromagnetic spectrum and would have to push out to lower or higher frequencies to send all of his messages.

- These limits were also something that engineers at AT&T, RCA, and other companies worried about in the middle of the 20th century, and to deal with increasing volume of messages (telephone calls, telegrams, television programs, and news), they experimented with both parsing the spectrum into smaller channels as well as expanding the spectrum by transmitting at higher and lower frequencies.
The means to overcome the fact that the electromagnetic spectrum is a finite resource came not from an engineer but, rather, a mathematician at Bell Labs: Claude Shannon.

During World War II, the U.S. government asked Bell Labs to come up with a way to encrypt telephone conversations between the United States and Britain that the Germans could not intercept and decode. Bell engineers came up with pulse code modulation (PCM).

Instead of sending a waveform down the wire, the engineers instead took thousands of samples per second of the value that the wave had, converted those into on/off pulses, and sent the string of on/off pulses down the wire. Done properly, the encoding/decoding could happen so quickly that the users on either end of a telephone conversation would never notice any processing delay.

While Bell Lab engineers got busy after the war converting PCM into a means for improving transmission quality, Shannon saw PCM as a way for him to rethink the nature of communications. In 1948, Shannon suggested that information could be measured in terms of bits and that bits could be expressed in terms of numbers—that is, digitally. The bits could be expressed in dots and dashes, the on/off pulses in PCM, or even in binary code—as ones and zeroes.

As a string of ones and zeroes, it became incredibly easy to speed up sending messages over a wire or across the airwaves, but Shannon went further and suggested that you could also compress messages by leaving out a portion of the message, provided that both the transmitter and receiver knew the rules by which portions were left out (i.e., a digital key). Compression would further enhance the speed by which information could now be sent.

**Getting Computers to Talk to One Another**

As Shannon pointed out, information can take any number of digital forms, but engineers soon settled on using binary code: ones and zeroes. Either something was “on” (1) or “off” (0).
• Binary code was particularly useful because it allowed computer engineers to build more sophisticated electronic computers because they could simply be huge aggregations of switches, on or off. But because nearly all electronic computers operated on some level on binary code, it opened the possibility of getting computers to talk to one another.

• In the 1960s, many universities and government agencies purchased large mainframes (like IBM’s all-transistor 360 system), but they soon discovered that they did not have enough work at hand to keep the machine busy (and warrant the initial cost of the computer).

• In response, some universities developed time-sharing arrangements whereby several institutions shared the capacity of a mainframe. To do so, researchers had to develop a file transfer protocol (FTP) whereby they could send programs and data over telephone lines from their home institution to the computer at another location.

• These procedures, known as packet switching, consisted of breaking the files down into manageable digital chunks (packets) and assigning an address to each. The packets could then be sent individually over the telephone line and reassembled at the receiving computer.

• Almost as an afterthought, the designers of these time-sharing systems added a feature that permitted users to send text messages to confirm receipt of electronic files or instructions to the people operating the mainframe.

• However, computer researchers soon discovered that this afterthought was a real convenience, and they began using it on a regular basis to communicate with one another. Hence, this afterthought evolved into email, and the first program for sending messages between computers on a network was put together by Ray Tomlinson in 1972.
To link all of the developing networks together, two computer researchers, Vinton Cerf and Bob Kahn, formulated a cross-network protocol that allowed packets to move from network to network. This internetworking of networks came to be known in computer lingo as the “Internet.”

The World Wide Web and Search Engines

Along with email, another important development was the creation of the means by which people could locate and access information from computers anywhere in the network. To do this, several software engineers—including Sir Tim Berners-Lee at the Center for Particle Research (CERN) in Geneva, Switzerland—developed what has come to be known as the World Wide Web.

To create the Web, Berners-Lee and others invented three things: a language (HTML) for assembling text, pictures, and files onto a webpage; a system of codes to give an address to every website and page (URL); and a protocol (HTTP) for moving Web files from their source (or server) to the user’s machine.

Combining words, pictures, sounds, and even video into a convenient and flexible package, the Web proved attractive to numerous individuals and businesses. Web access was improved by means of browsers developed at the University of Illinois (Mosaic) by Marc Andreesen, who subsequently commercialized Mosaic by launching Netscape, which millions of people used in order to surf the Web.

With millions and billions of possible places to look for a specific piece of information, it became apparent to several entrepreneurs that people needed some way to sort through and find what they wanted on the World Wide Web.

The first tool used for searching on the Internet, Archie, was created in 1990 by three computer science students at McGill University in Canada: Alan Emtage, Bill Heelan, and J. Peter Deutsch. Archie downloaded the directory listings of all the files located on public,
anonymous FTP sites and then generated a searchable database of file names.

- Rather than work from what was available on public lists, computer scientists next invented Web crawlers (sometimes known as spiders) that browse the entire Web in a methodical fashion. Based on Web crawlers, several search engines appeared in the 1990s, including Lycos, Excite, and Yahoo!.

- The most successful of these startups has been Google, which was created by two Stanford computer science Ph.D. students: Larry Page and Sergey Brin. While Yahoo! and its rivals used Web crawlers to collect data about websites, they were still relying on humans to index the data, and it was this data that was used to answer search inquiries from users.

- Page and Brin realized that they could significantly improve the search process by taking several steps. First, they decided

Both the Internet and the Web are revolutionary; these inventions have radically altered how we work and play.
to use Web crawlers to collect and store all or part of as many webpages as possible as well as information about who has viewed those webpages.

- Next, they made an assumption that the most useful or reliable pages are those that were viewed the most often and linked to other pages. Based on this assumption, they created an iterative algorithm that generates a PageRank, which is used to organize the listing of the sites that a user sees when he or she does a search on Google. As more people use the Web, and move from website to website, Google counts these hits, feeds them back into the algorithm, and updates the PageRanks.

- Page and Brin came up with the basic idea behind their algorithm in 1996 and launched a search engine under the name of BackRub, which was eventually changed to Google.

- By 2000, Google had indexed a billion webpages, making it the largest search engine on the Web. At the end of 2010, it had 84 percent market share of the search-engine business. Since 2000, Google has added a number of additional features: You can download maps and driving directions, search books from the libraries of Harvard and Oxford, and watch videos via YouTube—all for free.

- All of these features cost money to design and maintain, and Google makes money on advertising. While other search engines made money by running banner ads (which many users find annoying) and by listing advertisers higher up in the search results, Google has pursued two different revenue streams.

- Page and Brin realized that if people were going to enter a term in the search box, they might be looking for a product to buy and, hence, would be open to reading ads for items related to the search they were conducting. This led Google to create AdWords.
- When you conduct a search, you not only get the results from the search engine, but you also get a selection of ads. Companies arrange for Google to place these ads, and they only pay Google when the ad is shown to a user. In addition, because some words or products are especially popular, Google doesn’t just let anyone sign up for those spaces but, rather, auctions them off to the highest bidder, generating more revenue.

- Google also has AdSense. Suppose you teach yoga classes and have a website to attract customers. You can then sign up with Google, who will pay you to run ads for mats and yoga-related gear. As the owner of the yoga site, you don’t pay anything, but rather, the manufacturers of the yoga gear pay each time their ad is dropped onto a site.

### Suggested Reading

Abbate, *Inventing the Internet.*

Carlson, *Tesla.*


### Questions to Consider

1. What is the difference between digital and analog communications? Why does “going digital” represent such a significant breakthrough?

2. What had to happen to telephone networks before there could be an “internet revolution”?

3. How does Google actually make money when all of its services for consumers are free?
Inventions are not necessarily “finished” when they are put in the hands of consumers. Indeed, consumers often use new technologies in surprising ways and, in doing so, can profoundly alter our understanding of an invention. This lecture presents you with several episodes of political unrest, and in all cases, it is human action that determines the outcome of the struggle between oppression and freedom—not technology like social media, which may act as a catalyst for further action and outcome but cannot determine that outcome in opposition to any other.

Iran 2009

- In the Iranian uprising of 2009, Twitter and Facebook proved to be far more useful reporting than organizational tools. Journalists, professional and otherwise, used them effectively to distribute information and to mobilize sentiment beyond the regime’s clutches.

- However, inside Iran, Twitter and Facebook were not effective technologies for purposes of organization. Text messaging proved timelier than either of the above, and even that was less effective than word of mouth. More importantly, no technology served as a game changer. As Charles Krauthammer put it, “Twitter cannot stop a bullet … a determined regime that is oppressive, that will shoot, almost always wins.”

- This is exactly what happened in Iran in 2009. The Revolutionary Guards ruthlessly suppressed the demonstrations, and the Green Revolution withered and died.

- However, Internet use increased throughout the Arab world over the next few years. Could its growing presence reach some critical mass that might support the theory that technology played a deterministic role in later events?
Tunisia 2010

- In Tunisia, Twitter and Facebook again played an important part in casting light on events that the government tried to shroud with a media blackout. Even before widespread protests erupted, these technologies had been utilized by dissidents opposing censorship and the violation of human rights under Tunisian strongman Zine al-Abidine Ben Ali. Many of these dispersed voices were suppressed through intimidation and the confiscation of equipment—strategies made necessary by the government’s lack of complete control of the network itself.

- The blogger Lina Ben Mhenni endured threats and the theft of computers from her home (even before spontaneous uprisings began), using VPNS (virtual private networks) and proxy servers to circumvent the government’s efforts to restrain her. Then, on December 17, 2010, a fruit vendor, Mohamed Bouazizi, frustrated and humiliated by authorities interfering in his efforts to support his family, set himself on fire in the city of Sidi Bouzid.

- Word spread quickly, and bloggers picked up the story. Ben Mhenni made inquiries and posted what she learned on Facebook, Twitter, and her blog. When demonstrators took to the streets in Tunis, she joined them and reported her experiences online using images and video as well as text in her narrative.

- Soon, she attended protests across Tunisia, continuing to spread news online about the rebellion. Interestingly, the government lighted upon the strategy of using Facebook (albeit rudimentarily) as a means of funneling online protest into a central conduit where it could be tracked more easily by security forces.

- In early 2011, Ben Ali fled the country, bringing the regime to an end. Does this suggest a cause-and-effect relationship between the technology and the outcome?

- Ben Mhenni, a central figure in the use of social media during the revolution, doubts that technology played a critical role, much less a
determining one, in its outcome. In her scenario, it is human agency, specifically immolation and demonstrations, that determined the outcome of events—not technology.

- Furthermore, the available technology was utilized primarily as a reporting tool that spreads news about the demonstrations rather than an organizational mechanism of the movement itself.

- Finally, it is impossible to see these technologies as having a democratic or libertarian bend when their various characteristics are being utilized by both sides for their diametrically opposed objectives. Nonetheless, Mhenni did offer a hint that the situation might have been different in Egypt.

**Egypt 2011**

- As in Tunisia, it was the death of a previously anonymous individual that catalyzed opposition to a repressive regime. Hosni Mubarak’s security forces employed intimidation and murder for three decades, but no incident produced such an extreme response as did the death of 28-year-old Khaled Said, who was a businessman suspected of taking a video of Egyptian police officers using drugs.

- In June 2009, police dragged him out of an Internet café in Alexandria and beat him to death in the lobby of a nearby apartment building. Less than a week after his death, a “We Are All Khaled Said” Facebook page had been created, and within days, it had more than 130,000 members. When protests brought Cairo to a standstill 18 months later, Said’s case and Facebook page were still prominent in the minds of those attending the protests in Tahrir Square.

- During the period between the two events, Internet service and access to Facebook, Twitter, and other social networking sites had remained open. Egypt had the largest number of Facebook users in the region—more than five million—and many of them used this virtual public space to voice their opinions.
• As they did so, they coalesced into a movement that began to organize and mobilize activity on the ground. Invitations to street demonstrations were posted on the Said Facebook page in June 2010, and thousands of people attended. Protests continued on a more or less weekly basis through the fall. When in December and January the revolution in Tunisia led to the ouster of Ben Ali, general protests against the government broke out in Egypt.

• Three days after protesters took over Tahrir Square, the Internet was shut down inside of Egypt. However, under pressure from the U.S. State Department, at least some service was restored within five days.

• This is very different than the picture that emerged from Iran or Tunisia. In Egypt, Facebook and Twitter not only played an important role by spreading information, but also as a means of organizing the revolution itself.

• Furthermore, to the extent that Facebook served as the only available public space where opinions could be shared and bonds formed, one could make a pretty convincing argument that technology acted as a catalyst for revolutionary action. It might have contributed to the very large scale of the movement, a factor that probably influenced the Egyptian military to refrain from cracking down on the protests with a brutality similar to that seen in Iran.

One way to think about social media is to see them as “technologies of freedom.”
• However, it would be far too much to suggest that Facebook was the only factor, or even the most important one, in that decision. It would be equally baseless to assert that any inherent quality of the technology itself (its theoretically democratic nature) determined the outcome of the revolution.

**Weibo in China**

• Nowhere around the globe does the conflict between free speech and political oppression play out more profoundly in the technological environment than in China. As a BRIC country (Brazil, Russia, India, China), China is one of the world’s fastest-growing economies, but it has also been identified as one of the SICK countries (Syria, Iran, China, North Korea)—those that are the most politically oppressive.

• One of the newest tools in its arsenal of repression is the so-called Great Firewall of China. The most obvious purpose for erecting this barrier is to protect the regime from what are generally considered to be universal values associated with human rights and free speech. In reality, the effort to isolate Chinese netizens has proven to be more of an electronic Maginot Line than a Great Wall, but it also produced unexpected consequences and opportunities for authorities.

• As Internet use evolved in China, Beijing became far more sophisticated about the potential of technology to promote their political aims. When they cut China off from the Internet, they did not create dead virtual space; rather, they replaced the Internet with “Chinanet.” With the demise of Google, Facebook, Twitter, and YouTube came the birth of Chinese clones: Baidu, Renren, Weibo, and Youku, respectively.

• Today, Chinanet is a thriving electronic landscape with half a billion users and 300 million microbloggers using Weibo, which has become the country’s first public space—one that enjoys a greater degree of free speech than other parts of Chinese life.
• The incredible number of social networkers is a testament to the appeal of this environment, and contrary to what many would believe of an oppressive regime, Beijing has encouraged the growth of these numbers.

• That is because, unlike in other countries, the government controls every aspect of the servers and applications themselves, including the massive amount of user data they accumulate. That data is a powerful resource that can be mined as part of the central government’s effort not just to monitor, but also to exploit the discourse for its own purposes.

• Beijing sits at the center of the network—the hub at the center of the wheel. The spokes of the wheel can only communicate with one another through the hub. This allows Beijing to separate the population into disunited blocks, even as public discourse is increased.

• It also lets the central authorities continue a modern version of an ancient Chinese tradition: the petition of the emperor. This tradition exploited the image of the emperor as the ultimate symbol of good in comparison with corrupt local officials, the bane of the peasantry.

• Peasants could travel to the capital to directly petition the emperor for the redress of their grievances. However, in the modern world, where travel is so much easier, any system that directs complaints to central authorities in Beijing also runs the risk of flooding the city with a mass of unhappy citizens.

• Hence, the exploitation of a Weibo “petition”: an arrangement that promotes dependence of central authority and enhances its image of beneficence at the expense of local officials without concentrating discontent in a single physical location.

• Of course, because they possess administrative control over the system, Beijing can still shape the direction of the rumors and conversation—even ban it if necessary—as it did in August 2012,
when Weibo was shut down to remove posts containing rumors of a coup.

- Users know this and use a variety of puns and mimes to avoid censorship. Even so, any reference to a meeting, gathering, or assembly of any kind is mined, and police greet attendees as they arrive.

- However, this relates only to central, not local, authority because they don’t have the data. This being the case, local governments have become more “transparent”—perhaps an unintended consequence.

### Suggested Reading

Pool, *Technologies of Freedom*.

### Questions to Consider

1. Did social media, such as Twitter and Facebook, “cause” the Arab Spring uprisings? Why or why not?

2. The Chinese government is determined to control social media in the country; do you think that they will succeed, or are modern communications technologies inherently democratic?
Throughout this course, you have considered major inventions that have been disruptions—making and breaking empires, empowering different groups of people, creating whole new industries, and altering everyday life. You have learned about a wide array of inventions, spanning civilizations from the ancient Near East to China, Europe, and America. You have learned about inventions, including stone tools from 500,000 years ago to the social media that are shaping political change in the 21st century. Some of the inventions that have been addressed would be on anybody’s list of great inventions—the steam engine, the Model T, and the Internet—and, hopefully, some have been surprises, such as canning food, department stores, surgery, or nickelodeon theaters.

The Quest of Historians

- One way of looking at the rich array of human creativity is to see it as a long series of isolated events—isolated both in the sense that each episode of invention is separate from others and in the sense that each invention doesn’t necessarily have anything to do with the social or cultural environment surrounding it.

- However, historians seek patterns across human experience, and that’s what this course has been doing as it has moved from lecture to lecture. One simple way that the stories are connected is that a person can often be tracked from one invention to another. For example, Leonardo da Vinci turns up in a number of stories, ranging from clocks to canal locks to aviation.

- Another example is that Thomas Edison worked on several major inventions—including the telephone, the phonograph, electric lighting, and motion pictures—and he provoked Nikola Tesla as well as inspired Henry Ford. Equally, the evolution of microchip technology was narrated in terms of the different jobs held by

- At other times, inventors leverage the capability of a new device or material to create additional inventions and whole new industries. For example, annoyed by the inefficiency of the Newcomen steam engine, James Watt developed his improved engine with a separate condenser.

- In addition, iron and coal gave rise to new industries such as the railroad and textile manufacture. Furthermore, household appliances came about through the confluence of mass-production techniques pioneered by the auto industry, cheap power provided by electrical utilities, and distribution techniques made available by department stores.

Categorizing Inventions

- Another way to see patterns across inventions is to recognize that they take different forms and have different kinds of impact. These patterns grow out of several different categories.

- Some inventions are great because they create a dramatic increase the amount of food, energy, or information that various societies enjoy. These inventions include the following.
  - Brewing
  - Waterwheels
  - Coal and iron
  - Food preservation
  - The electric generator
  - Radio and television
  - Nuclear power
The personal computer and the Internet

- Other inventions are terrific examples of creativity and are technical tours de force. We might be tempted to think that these are only recent inventions, but indeed we can find them throughout history. Sometimes we know who created them, and sometimes we can only marvel at the ingenuity that is apparent when we study them closely. These inventions include the following.
  - The potter’s wheel
  - The crossbow in China
  - Printing in both China and Europe
  - The telescope and microscope
  - Thomas Newcomen’s steam engine
  - Alessandro Volta’s electric battery
  - Nikola Tesla’s alternating current motor
  - The Wright brothers’ airplane
  - Kary Mullis’s polymerase chain reaction

- These inventions are, from a creative standpoint, on par with the most important works of art, literature, and science, and a person can’t really claim that he or she is liberally educated unless he or she has a sense of how these devices work and how they changed the world.

- Another group of inventions that should be singled out are those that deeply reflect the values of the cultures in which they appeared. Among the examples that this course has addressed are as follows.
Lecture 36: Inventions and History

- Aqueducts and the Colosseum from Roman times
- Pagodas and cathedrals from the Middle Ages in both East Asia and Europe
- Aviation and nuclear power (how both were affected by military and political goals in the 20th century)

Classifying inventions in this way helps us appreciate that inventions not only have economic impact (i.e., generate more energy and more products), but they also embody social and cultural values.

The Economics and Science of Invention

- In addition to classification, we can ask about causes. Why do inventors invent? While the motivation of individuals varies significantly from case to case, we can ask two general questions: Are inventors driven by economic or market forces? What is the role of science in invention?

- Behind the familiar saying, “Necessity is the mother of invention,” is a notion that inventions come about largely as a result of some preexisting economic need—that people just “need” or want more energy or faster transportation or more television shows to watch.

- However, what you have learned in many of these lectures is that it can be difficult to connect a new invention with preexisting needs. Inventors often come up with something that initially no one really wants, so the real creative act can be connecting the invention with some use—be it preexisting or new.

- A great example is that the U.S. Navy didn’t really need nuclear propulsion after World War II, but Hyman Rickover pushed it through. Another example is that Ted Hoff could see the great potential for a microprocessor chip, but it took him two to three years to convince his bosses at Intel that they ought to start manufacturing them.
• In economic parlance, the biggest, most disruptive inventions are often not “demand-pull” but “supply-push,” meaning that they come about not because people are necessarily clamoring for a new invention, but instead, they grow out of the evolving knowledge and motivations possessed by inventors.

• Along with economic necessity, another common assumption that people have about inventions is that they are frequently the product of science. Scientists discover new phenomena and formulate theories, and inventors and engineers apply those discoveries to human needs.

• To be sure, there are occasionally cases where scientific inquiry results in a new invention—for example, the battery, the transistor, or genetic engineering—but in other cases, the distance between theory and practice is significant, and there’s a great deal of hard engineering that needs to be done to go from the laboratory benchtop to a product that people use every day.

• Think about what it took to go from Michael Faraday’s ideas about electromagnetic induction to the electric power systems of the early 20th century or from Heinrich Hertz’s discovery of radio waves to radio broadcasting. Think about the role of DuPont engineers in converting atomic theory into atomic bombs.

• Instead, it can be argued that many inventions grow out of craft knowledge and experience—the sort of knowhow that inventors accumulate as they think about and manipulate ideas and objects.

• Edison, for example, got ahead of Alexander Graham Bell on the telephone because Edison had years of experience messing with telegraph circuits and because he knew how to shape a material like carbon lampblack into a better microphone transmitter.

• Likewise, the Wright brothers were the first to fly not because they possessed some esoteric theory, but because they could take advantage of their experience with how riders kept bicycles steady
as well as a willingness to test new wing shapes (airfoils) in a homemade wind tunnel.

- One might challenge this claim that invention is more about hands-on knowledge than it is about scientific theory by pointing out that companies in the 20th century hired many scientists and created research and development labs for them. Certainly, Bell Labs is a great example of such an organization, producing the transistor and much of the technology underlying cell phones.

- However, it could be argued that scientists are creative in the research and development environment because they possess a high level of experimental skill—that they can handle test tubes, instruments, and complex apparatuses in ways that allow them to manipulate phenomena better than other people. It’s the experimental skill, more than the theory, that brings home the technological bacon.

- As you study inventions, you have to be willing to learn about machines; you have to be willing to think about technology not just...
as an idea, but as material embodiment of ideas that we experience with our bodies; and you have to be flexible in terms of your ideas about human nature and history.

- It is important to study great inventions not so much as to predict the future, but to understand human experience. For example, for the West, technology has been a major part of culture for the past 200 years. How did this come to pass? Technology is not outside culture and society but inside it; it is one of the most powerful ways that people manifest politics, beliefs, and meaning.

**Suggested Reading**

Hughes, *Human-Built World*.

Nye, *Technology Matters*.

**Questions to Consider**

1. In looking at all of the inventions in this course, what does it mean to say that there has been progress? What are we highlighting when we talk about progress? What are we downplaying?

2. What are some of the factors that influence the creation of new inventions?

3. If you were to make three predictions about future inventions, what would they be? Abbate, Janet. *Inventing the Internet*. Cambridge: MIT Press, 1999. Traces the development of packet switching.


multivolume *History of Technology*, this set covers an interesting range of technologies, touching on topics not covered by Singer.


Hughes, Thomas P. American Genesis: A Century of Invention and Technological Enthusiasm. New York: Viking, 1989. One of the few sources that discusses the role played by DuPont and its engineers in developing the atomic bomb during World War II.


Powledge, Tabitha M. “The Polymerase Chain Reaction.” *Advances in Physiology Education* 28, no. 2 (June 1, 2004): 44–50. Provides an accessible description of how PCR works and some of its applications.


survey of the development of electric generators, motors, and lights in the early to mid 19th century.


